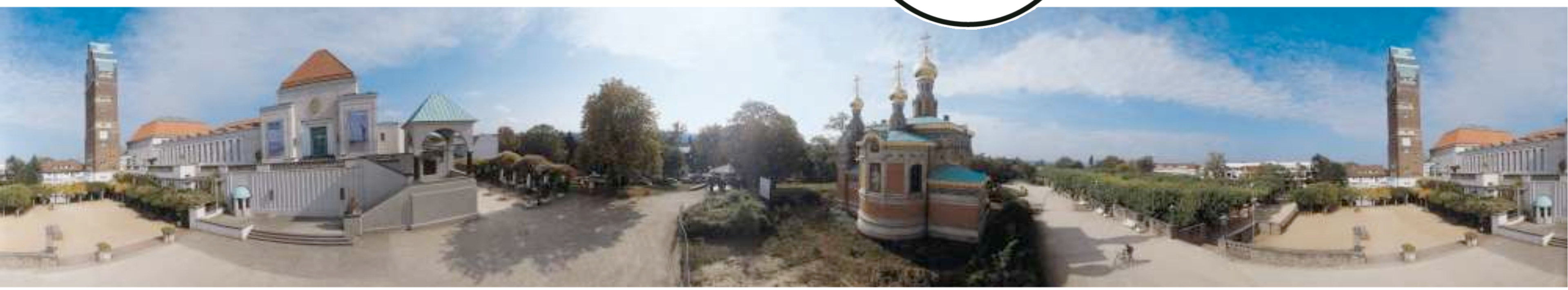
Three-nucleon forces at neutron-rich extremes

Achim Schwenk

TECHNISCHE UNIVERSITÄT DARMSTADT

EMMI



George Bertsch Fest

Seattle, Sept. 8, 2012

S-DALINAC

DFG

erc

HELMHOLTZ | ASSOCIATION

Minerva Stiftung

ARCHES

Award for Research Cooperation and High Excellence in Science

Bundesministerium für Bildung und Forschung

Happy Birthday George!

Outline

Understanding three-nucleon (3N) forces

3N forces and neutron-rich nuclei
with **J.D. Holt, J. Menendez**, T. Otsuka, T. Suzuki

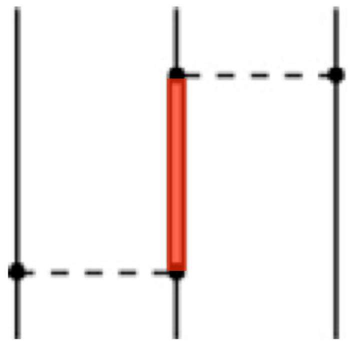
3N forces and neutron matter/stars
with **K. Hebeler, T. Krüger, I. Tews,**
J.M. Lattimer, C.J. Pethick

Electroweak interactions and 3N forces
with **J. Menendez**, D. Gazit

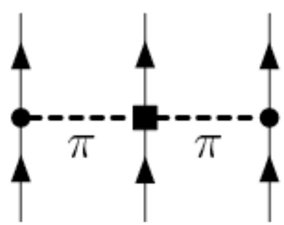
Why are there three-nucleon (3N) forces?

Nucleons are finite-mass composite particles,
can be excited to resonances

dominant contribution from Δ(1232 MeV)



+ many shorter-range parts

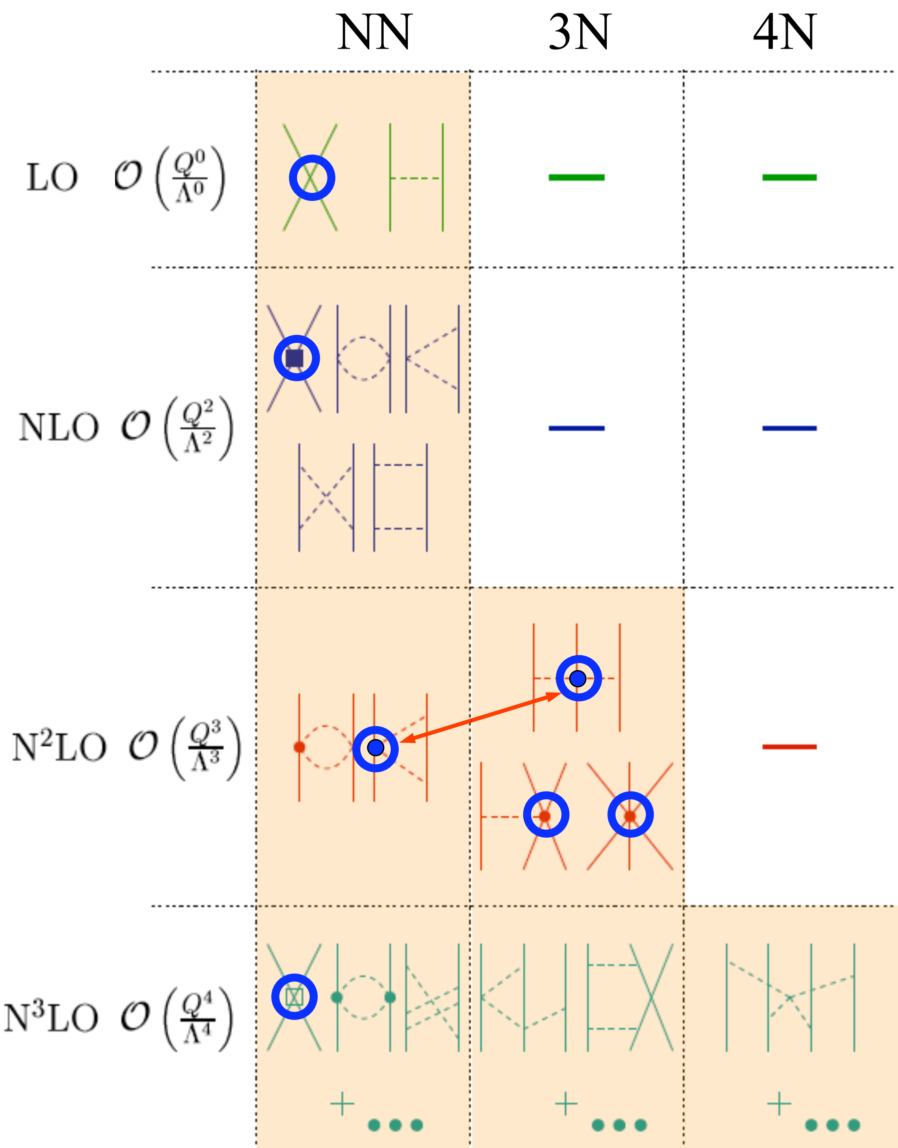
chiral effective field theory (EFT)
Delta-less (Δ is treated as heavy): 

+ shorter-range parts

EFT provides a systematic and powerful approach for 3N forces

Chiral Effective Field Theory for nuclear forces

Separation of scales: low momenta $\frac{1}{\lambda} = Q \ll \Lambda_b$ breakdown scale ~500 MeV



include long-range pion physics

few short-range couplings,
fit to experiment once

systematic: can work to desired accuracy and obtain error estimates

expansion parameter ~ 1/3

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…

Chiral Effective Field Theory for nuclear forces

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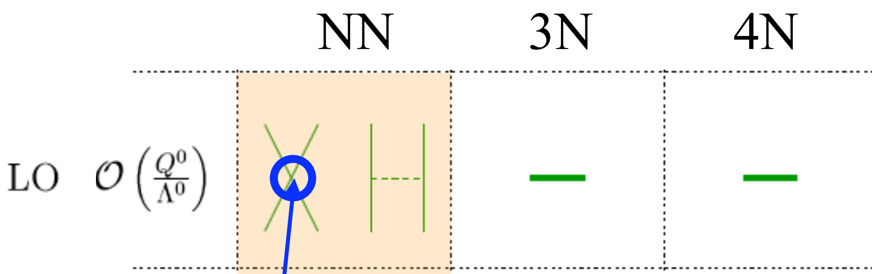
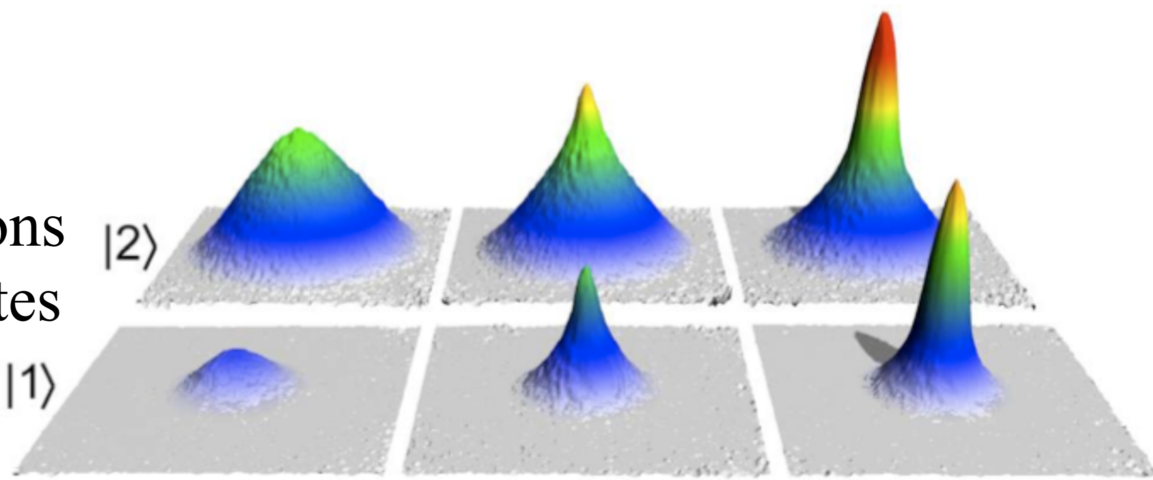


large scattering length physics – **The Bertsch problem**

^{6}Li fermions
2 spin states



from M. Zwierlein

neutrons with same density, temperature and spin polarization
have the same properties!

Chiral Effective Field Theory for nuclear forces

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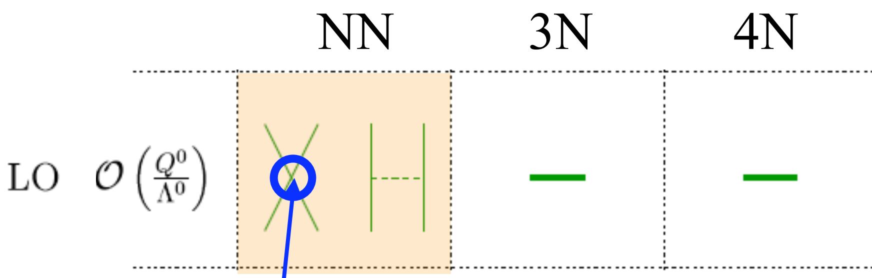


large scattering length physics – **The Bertsch problem**

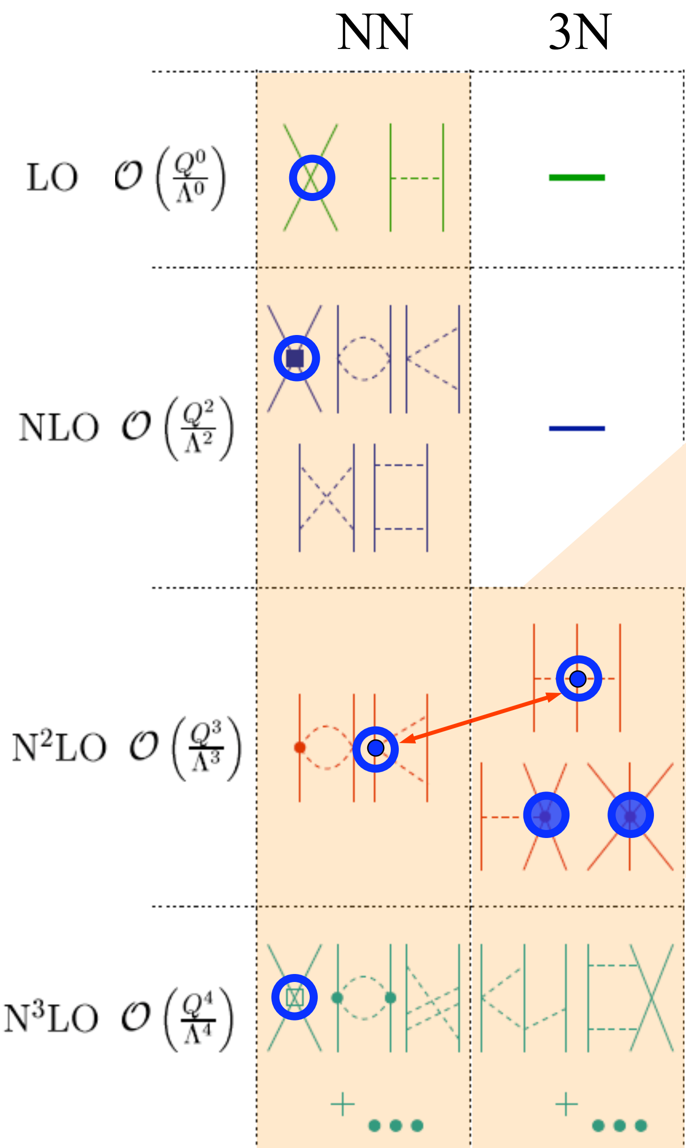
As $T \to 0$, the Fermi energy E_F is the only intensive energy scale, so the chemical potential must be related to E_F by a universal number, $\mu = \xi E_F$, where ξ is known as the Bertsch parameter

Science AAAS

Revealing the Superfluid Lambda Transition in the Universal Thermodynamics of a Unitary Fermi Gas
Mark J. H. Ku, *et al.*
Science 335, 563 (2012);
DOI: 10.1126/science.1214987

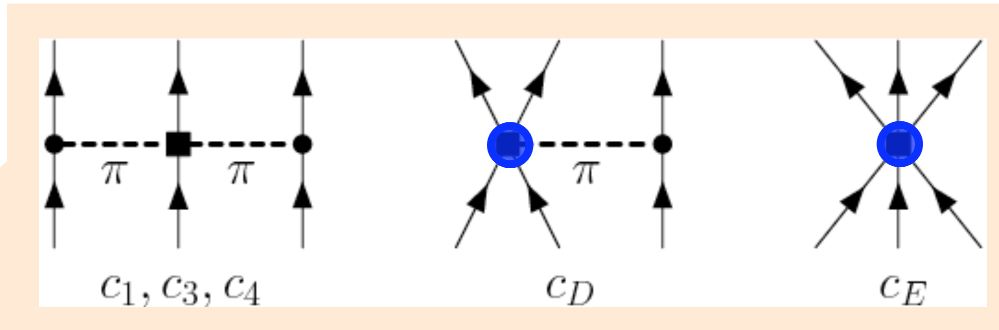
Chiral Effective Field Theory and many-body forces

Separation of scales: low momenta $\frac{1}{\lambda} = Q \ll \Lambda_b$ breakdown scale ~500 MeV



consistent NN-3N interactions

3N,4N: only 2 new couplings to N^{3}LO



c_i from πN and NN Meissner et al. (2007)

$$\boxed{c_1 = -0.9^{+0.2}_{-0.5}\,,\; c_3 = -4.7^{+1.2}_{-1.0}\,,\quad c_4 = 3.5^{+0.5}_{-0.2}}$$

single-Δ: c_1=0, c_3=-c_4/2=-3 GeV^{-1}

c_D, c_E fit to ^{3}H binding energy and ^{4}He radius (or ^{3}H beta decay)

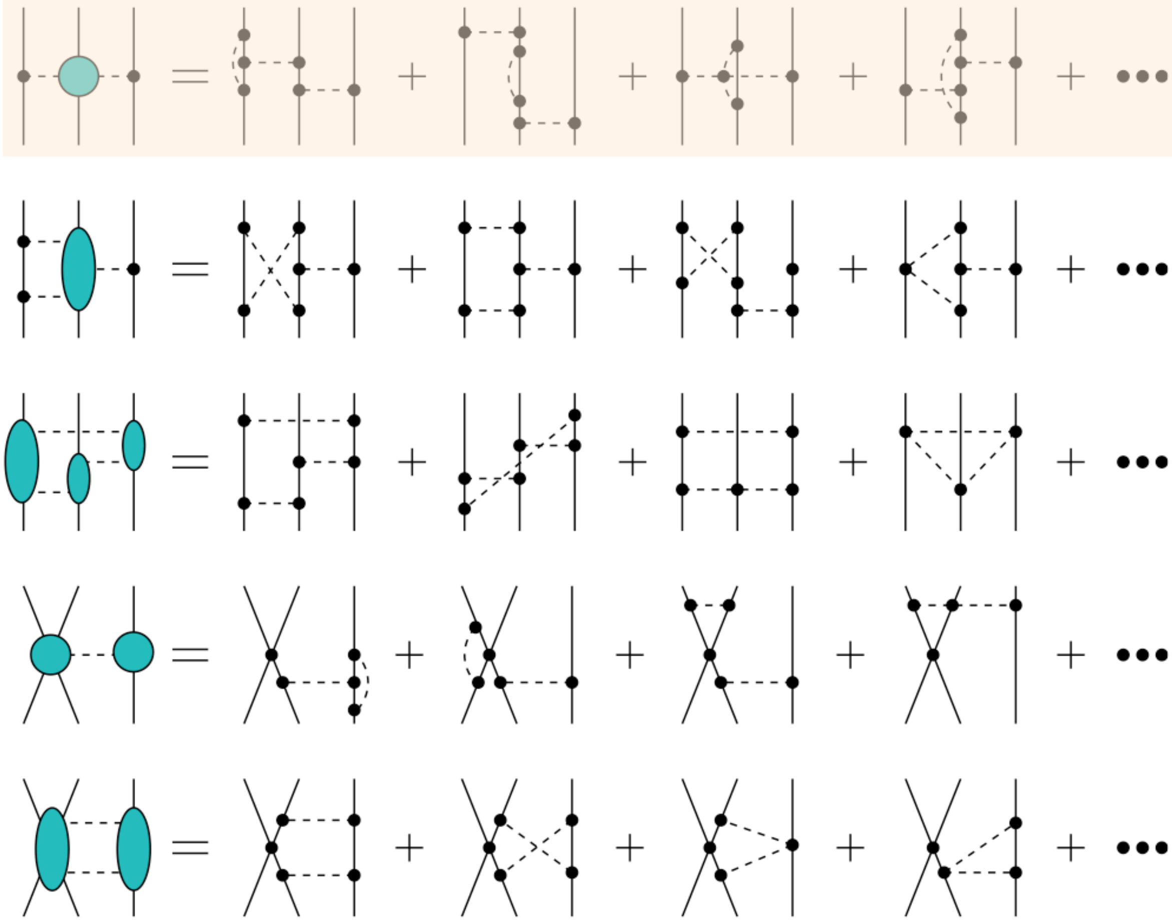
Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…

Subleading chiral 3N forces

parameter-free N^3LO Bernard et al. (2007,2011), Ishikawa, Robilotta (2007)

one-loop contributions:

2π-exchange, 2π-1π-exchange, rings, contact-1π-, contact-2π-exchange



decrease c_i strengths

$\delta c_3 = -\delta c_4 = 1\ \mathrm{GeV}^{-1}$

comparable to

N^2LO uncertainty

1/m corrections: spin-orbit parts, interesting for A_y puzzle

Chiral Effective Field Theory for nuclear forces

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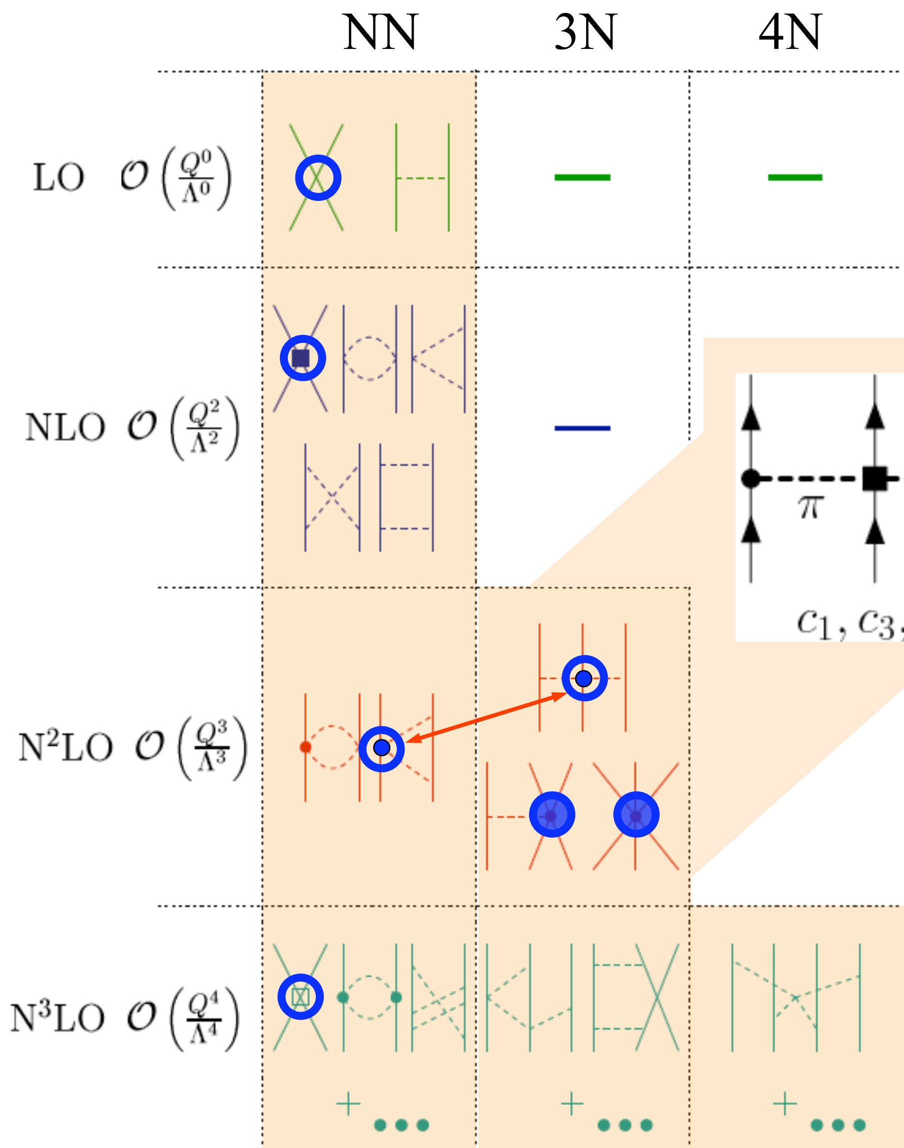
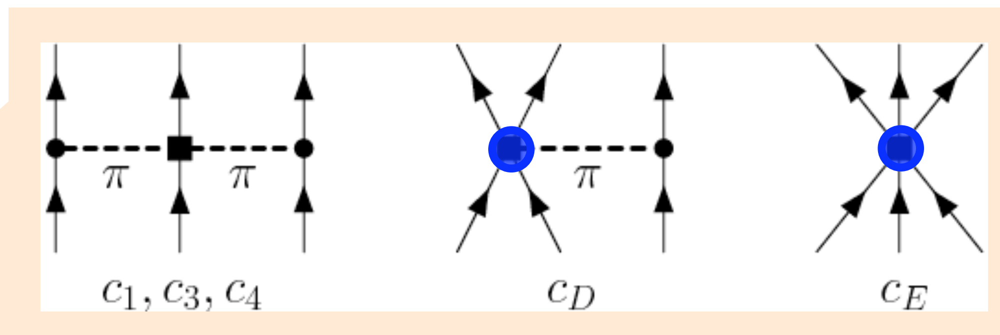


c_D, c_E don't contribute for neutrons because of Pauli principle and pion coupling to spin, also for c_4

Hebeler, AS (2010)



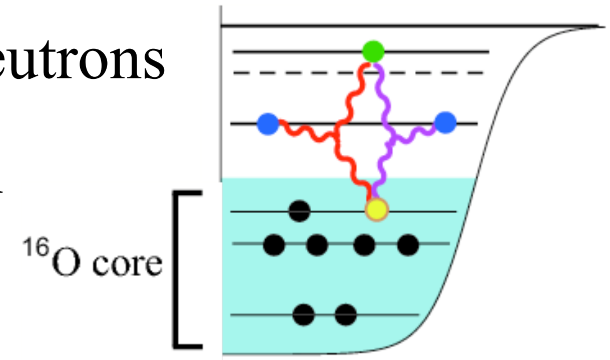
all 3- and 4-neutron forces are predicted to N^{3}LO!

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…

The shell model - impact of 3N forces

include ‘normal-ordered’ 2-body part of 3N forces (enhanced by core A)

leads to repulsive interactions between valence neutrons



contributions from residual three valence-nucleon interactions suppressed by $E_{ex}/E_F \sim N_{valence}/N_{core}$
Friman, AS (2011)

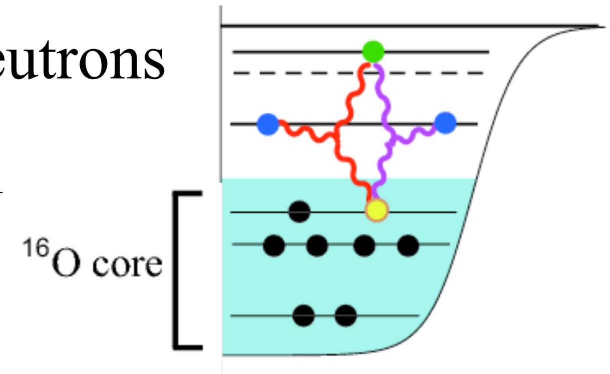
residual 3N amplified in most neutron-rich nuclei C. Caesar, J. Simonis et al. (2012)

Oxygen isotopes - impact of 3N forces

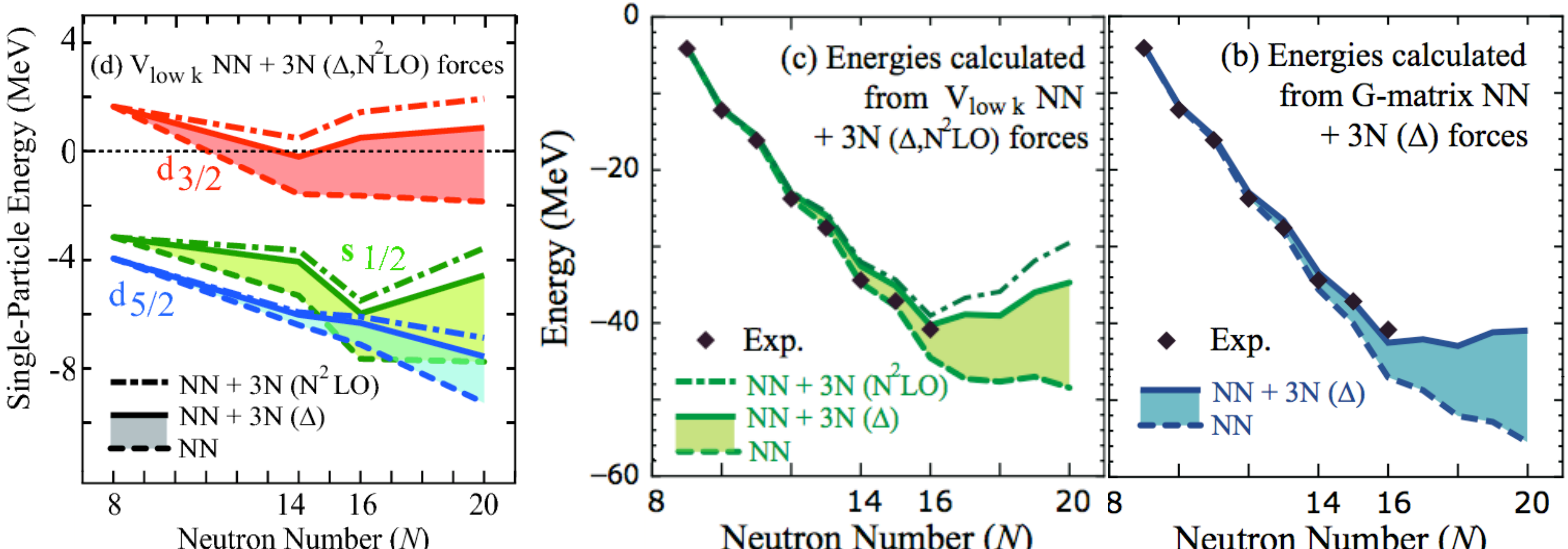
include 'normal-ordered' 2-body part of 3N forces (enhanced by core A)

leads to repulsive interactions between valence neutrons

contributions from residual three valence-nucleon interactions suppressed by $E_{ex}/E_F \sim N_{valence}/N_{core}$
Friman, AS (2011)



$d_{3/2}$ orbital remains unbound from ^{16}O to ^{28}O



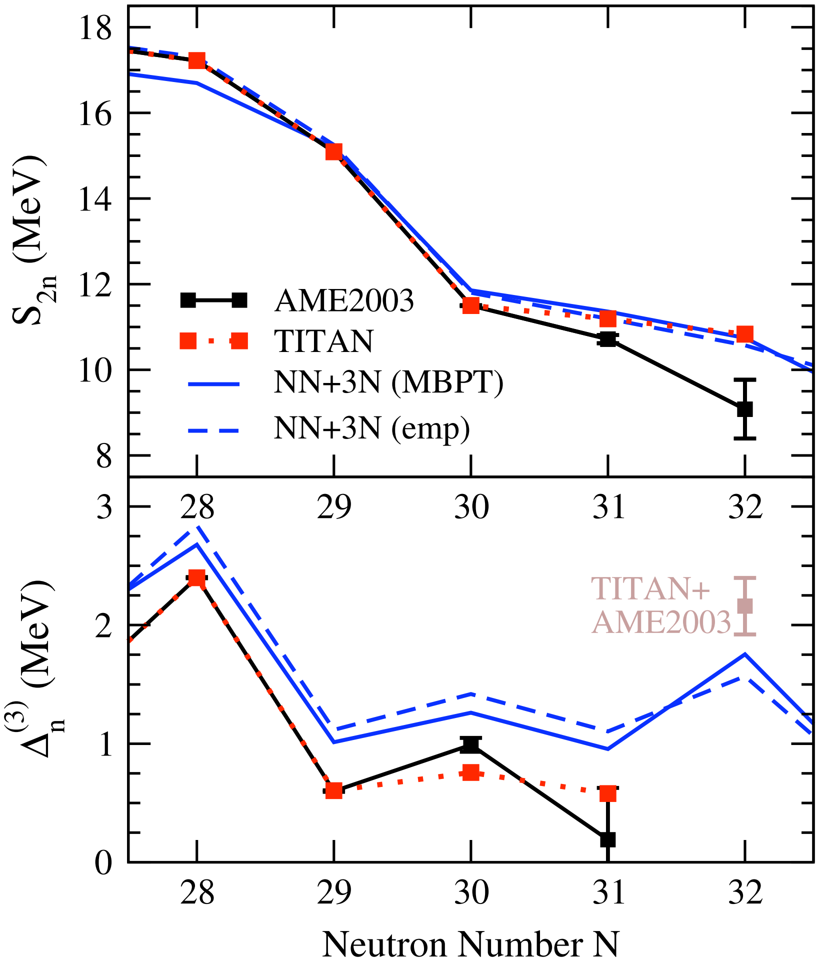
microscopic explanation of the oxygen anomaly Otsuka et al. (2010)

new ^{51,52}Ca TITAN measurements

^{52}Ca is 1.75 MeV more bound compared to atomic mass evaluation

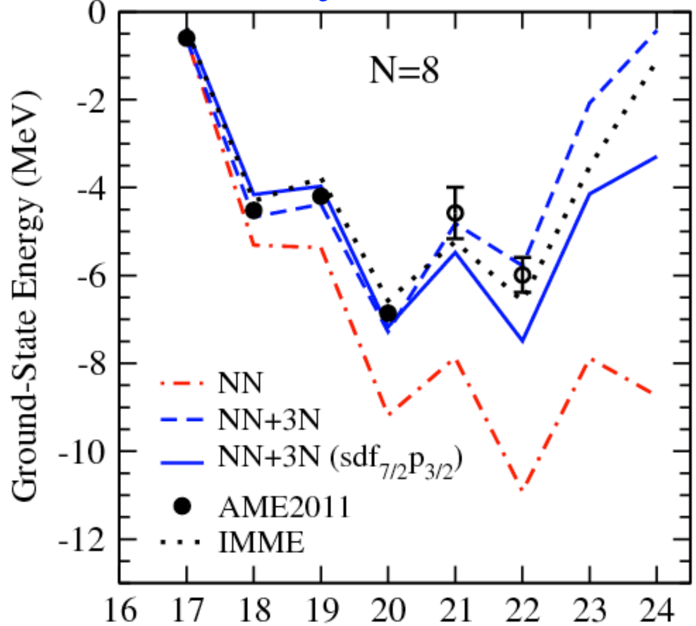
Gallant et al. (2012)

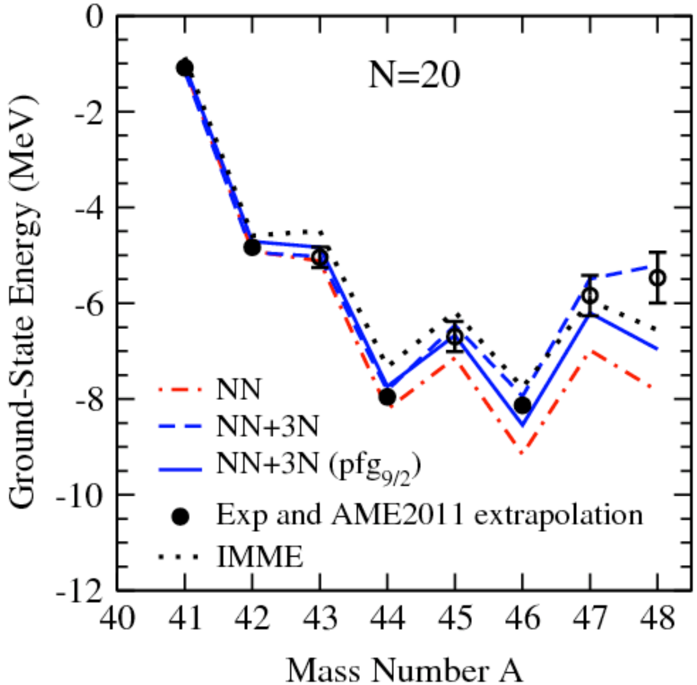
behavior of two-neutron separation energy S_{2n} and odd-even staggering Δ_n agrees with NN+3N predictions

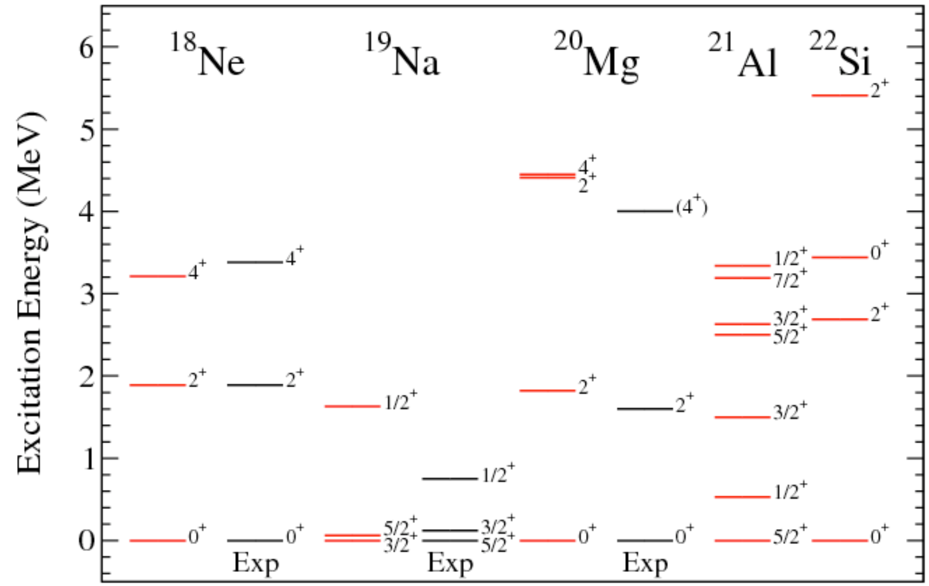


Three-body forces and proton-rich systems

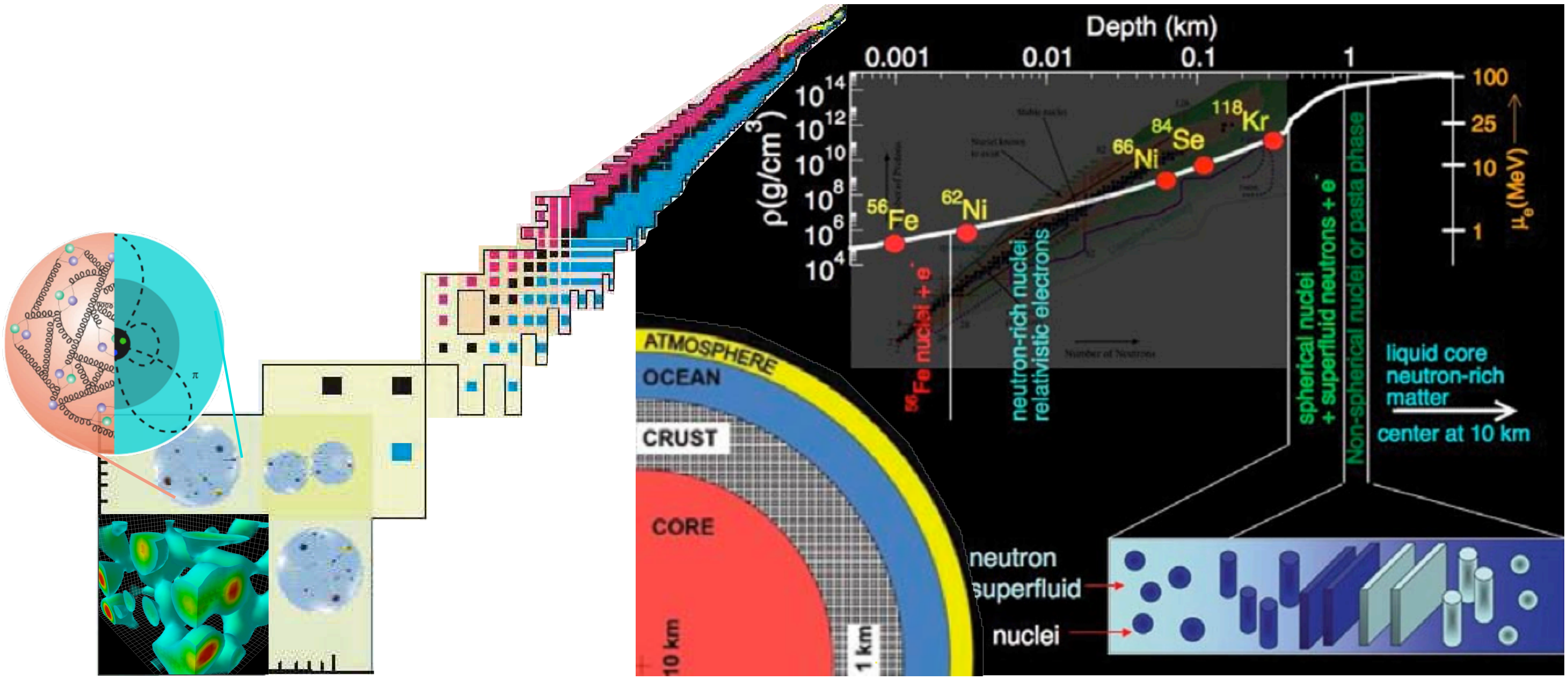
Holt, Menendez, AS







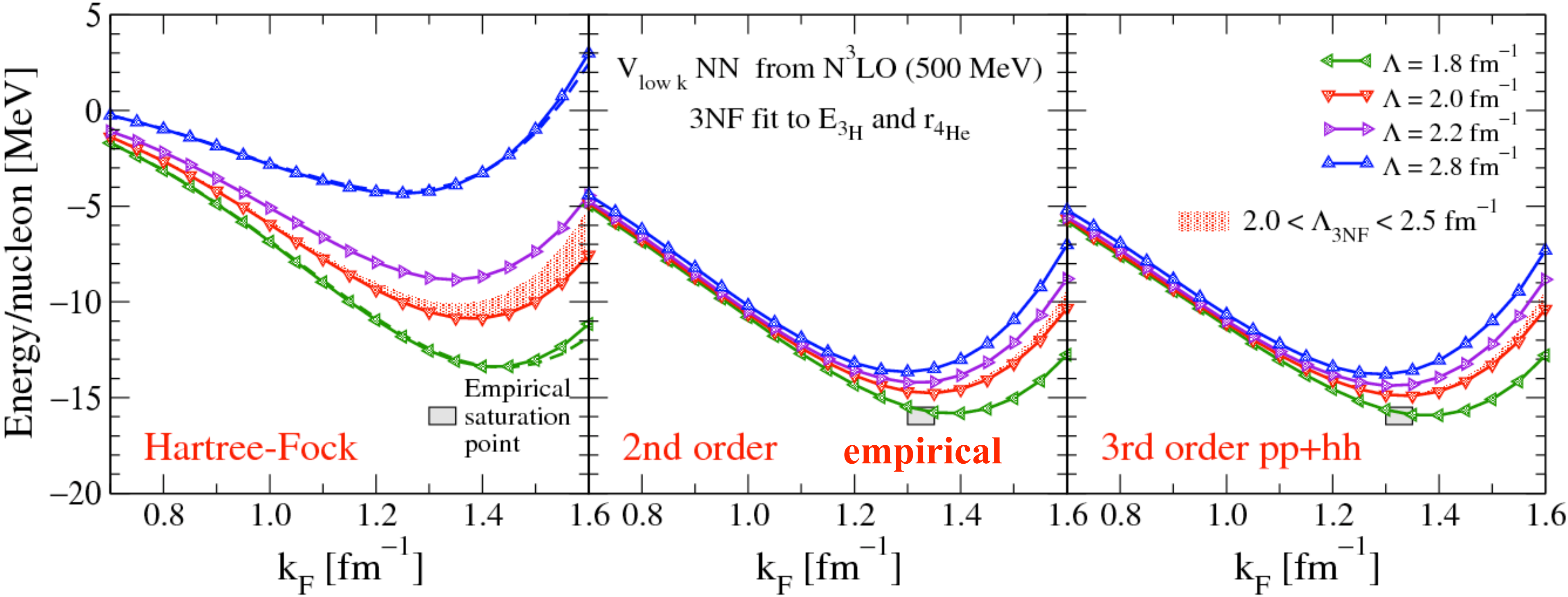
Neutron matter and neutron stars



Impact of 3N forces on nuclear matter

chiral 3N forces fit to light nuclei
predict nuclear matter saturation
with theoretical uncertainties

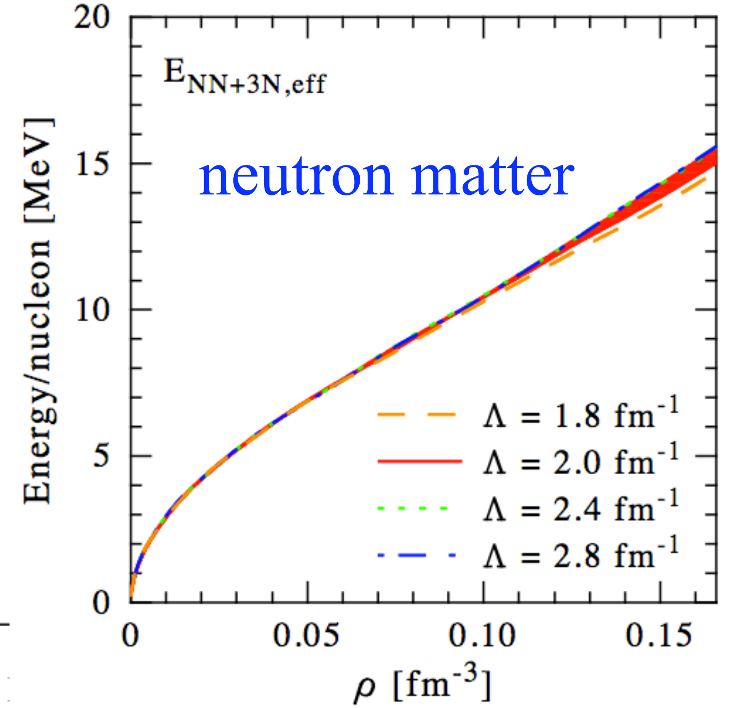
Hebeler et al. (2011), Bogner et al. (2005)

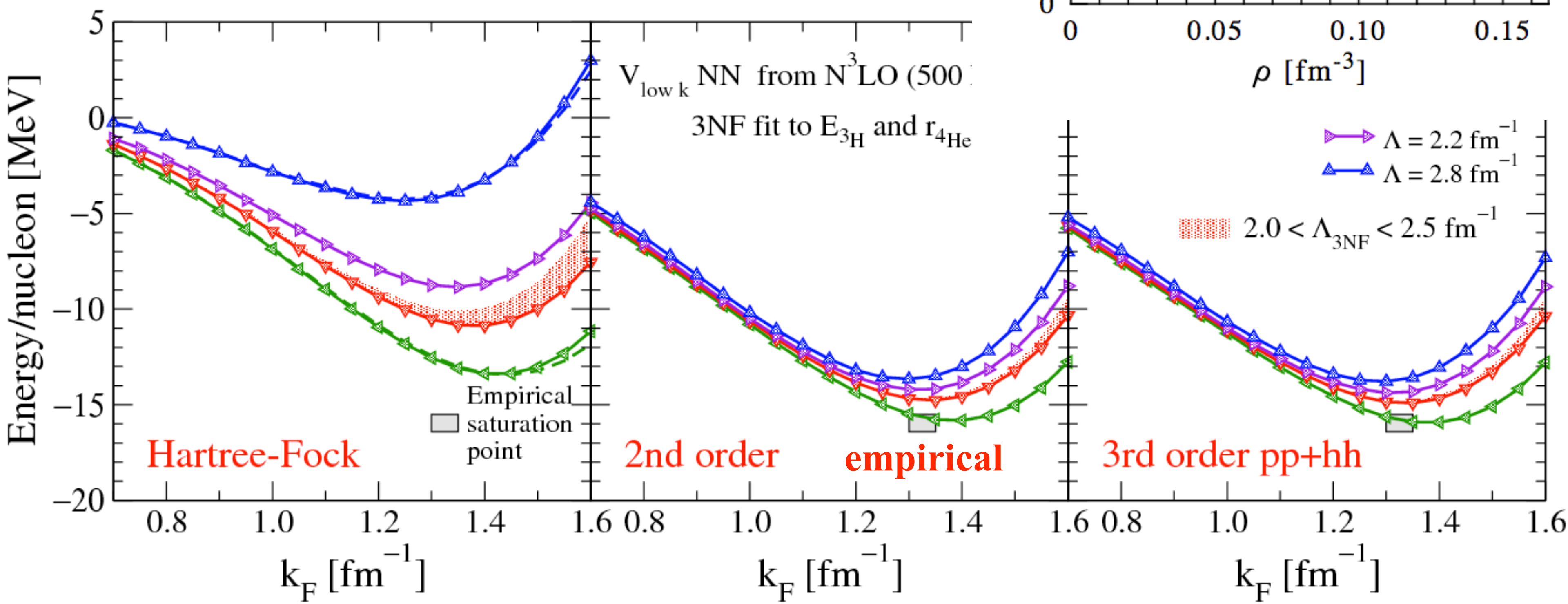


Impact of 3N forces on neutron matter

neutron matter is simpler system,
only long-range parts of 3N forces
contribute (c_1 and c_3)

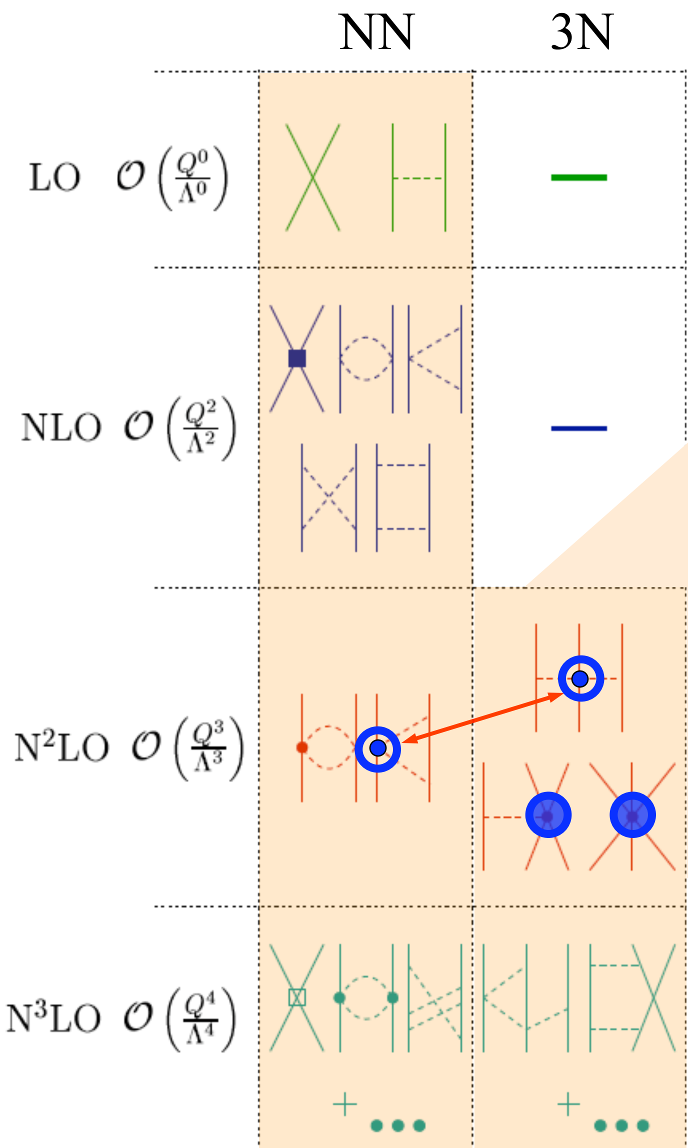
Hebeler, AS (2010)





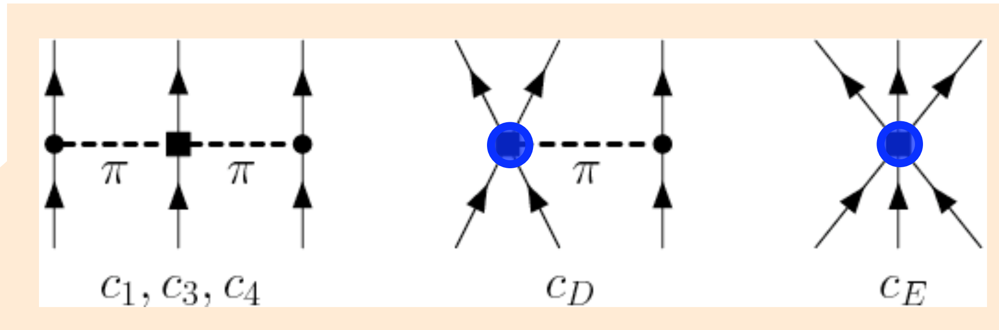
Chiral Effective Field Theory and many-body forces

Separation of scales: low momenta $\frac{1}{\lambda} = Q \ll \Lambda_b$ breakdown scale ~500 MeV



consistent NN-3N interactions

3N,4N: only 2 new couplings to N^{3}LO



long-range 3N: c_i from πN and NN

$$c_1 = -0.9^{+0.2}_{-0.5}\,, \quad c_3 = -4.7^{+1.2}_{-1.0}\,, \quad c_4 = 3.5^{+0.5}_{-0.2}$$

3- and 4-neutron forces are predicted to N^{3}LO ($c_{D,E}$ don't contribute)

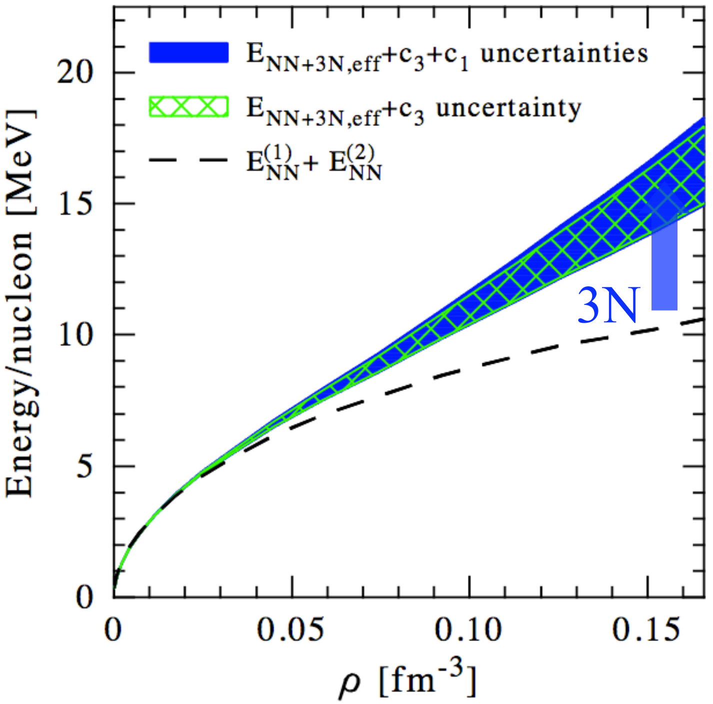
Hebeler, AS (2010)

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…

Impact of 3N forces on neutron matter

neutron matter uncertainties
dominated by 3N forces (c_3 coupling)

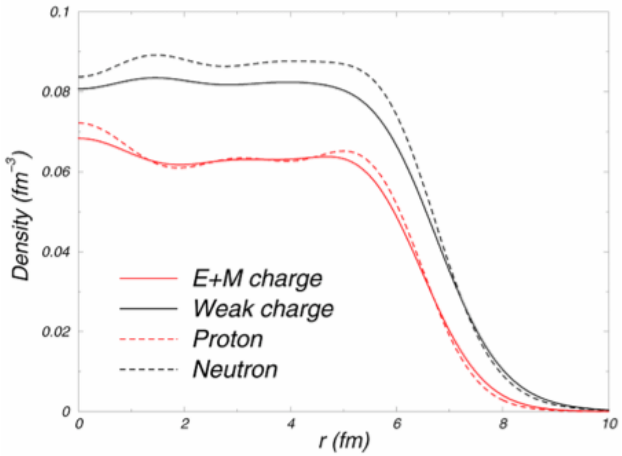
Hebeler, AS (2010)



Neutron skin of ^{208}Pb

probes neutron matter energy/pressure,
neutron matter band predicts
neutron skin of ^{208}Pb: 0.17±0.03 fm

Hebeler et al. (2010)



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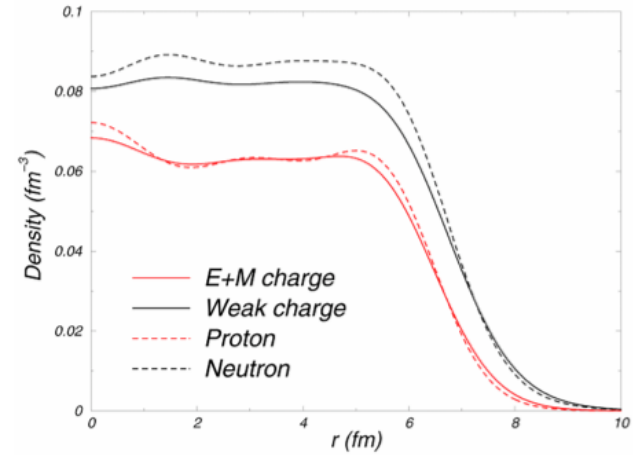


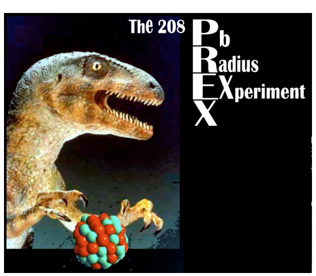
in excellent agreement with extraction from complete E1 response
0.156+0.025-0.021 fm

PRL **107,** 062502 (2011) PHYSICAL REVIEW LETTERS week ending 5 AUGUST 2011

Complete Electric Dipole Response and the Neutron Skin in ^{208}Pb

A benchmark experiment on ^{208}Pb shows that polarized proton inelastic scattering at very forward angles including 0° is a powerful tool for high-resolution studies of electric dipole ($E1$) and spin magnetic dipole ($M1$) modes in nuclei over a broad excitation energy range to test up-to-date nuclear models. The extracted $E1$ polarizability leads to a neutron skin thickness $r_{\rm skin} = 0.156^{+0.025}_{-0.021}$ fm in ^{208}Pb derived within

PREX: neutron skin from parity-violating electron-scattering at JLAB
electron exchanges Z-boson, couples preferentially to neutrons
goal II: ±0.06 fm



PRL **108,** 112502 (2012) PHYSICAL REVIEW LETTERS week ending 16 MARCH 2012

Measurement of the Neutron Radius of ^{208}Pb through Parity Violation in Electron Scattering

We report the first measurement of the parity-violating asymmetry $A_{\rm PV}$ in the elastic scattering of polarized electrons from ^{208}Pb. $A_{\rm PV}$ is sensitive to the radius of the neutron distribution (R_n). The result $A_{\rm PV} = 0.656 \pm 0.060({\rm stat}) \pm 0.014({\rm syst})$ ppm corresponds to a difference between the radii of the neutron and proton distributions $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm and provides the first electroweak observation of the neutron skin which is expected in a heavy, neutron-rich nucleus.

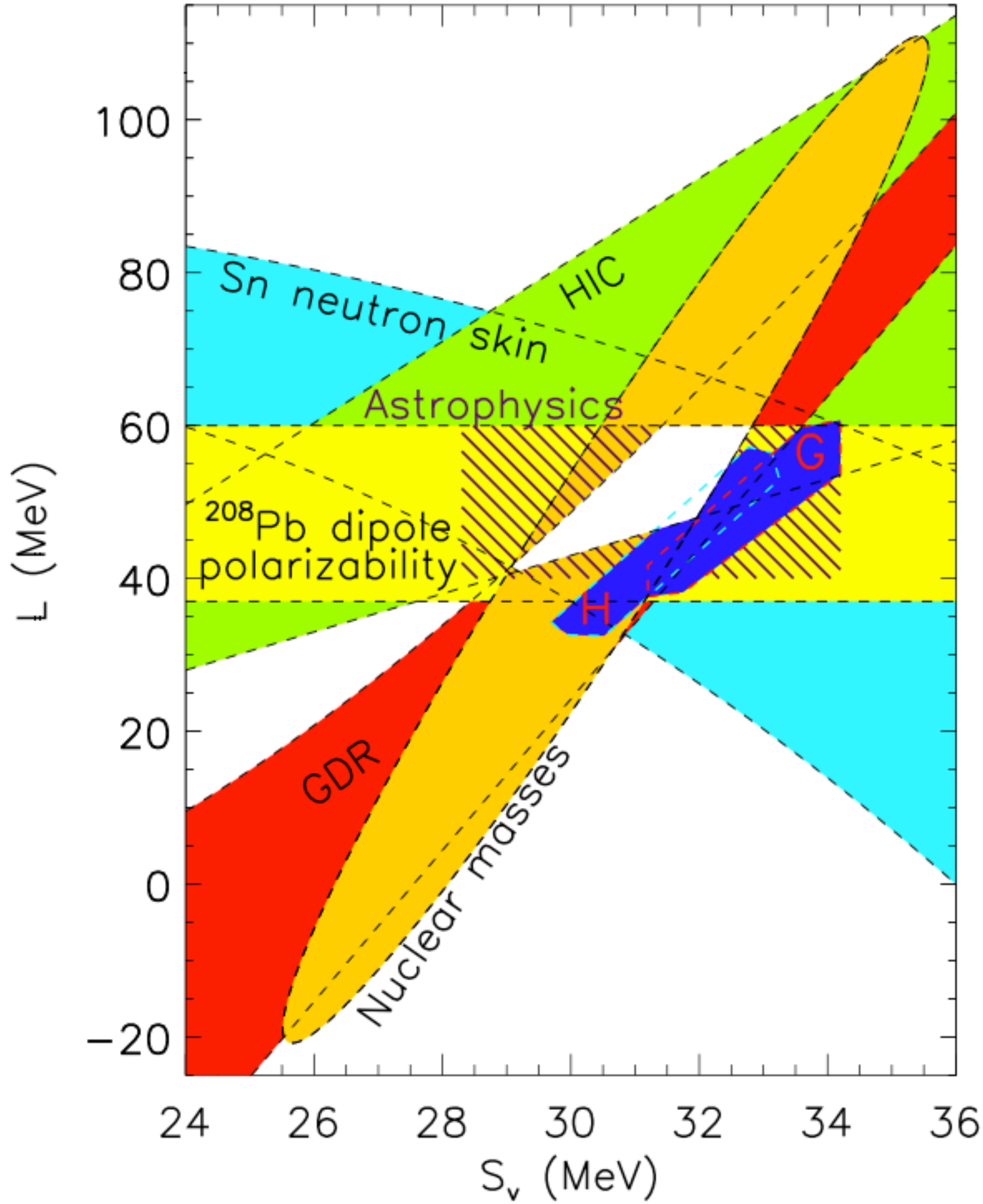
Symmetry energy and pressure of neutron matter

neutron matter band predicts
symmetry energy S_v and
its density dependence L

comparison to experimental
and observational constraints
Lattimer, Lim (2012)

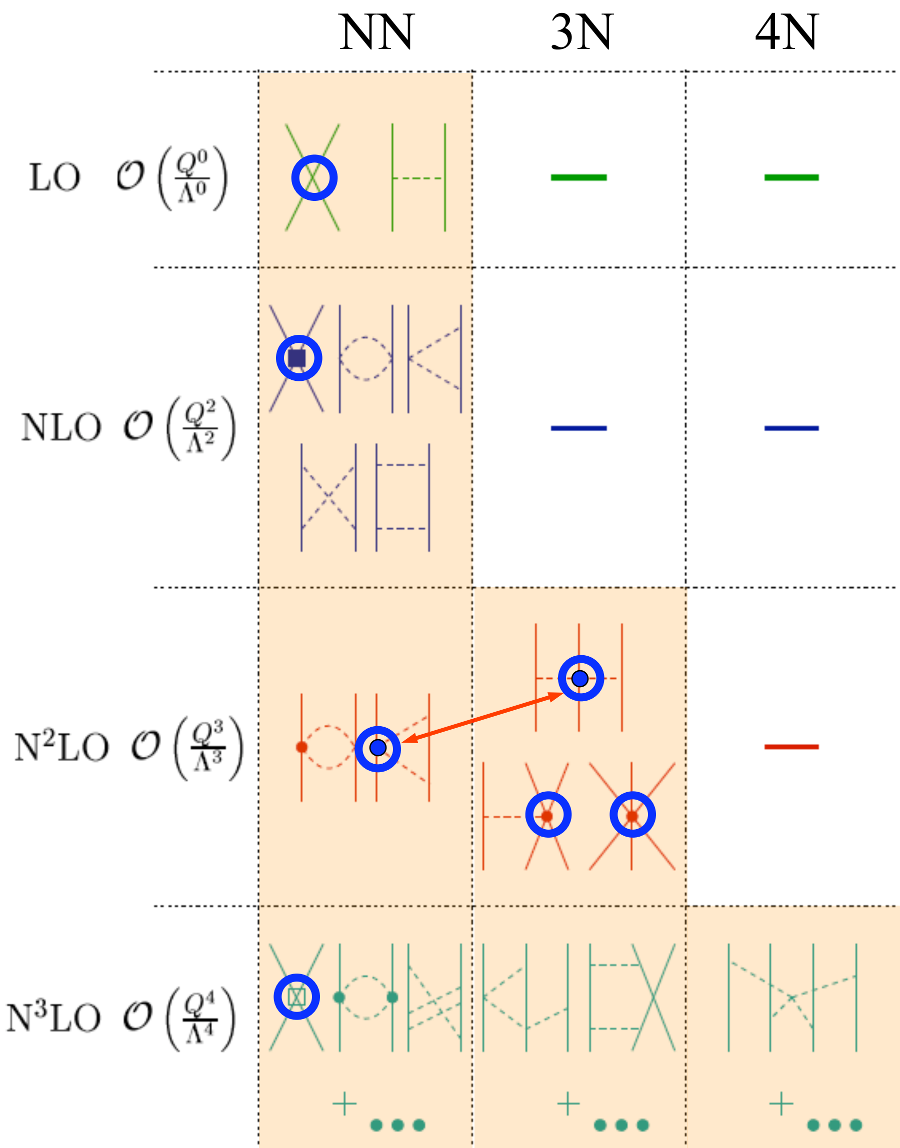
neutron matter constraints
H: Hebeler et al. (2010) and in prep.

G: Gandolfi et al. (2011)
predicts correlation
but not range of S_v and L



Chiral Effective Field Theory for nuclear forces

Separation of scales: low momenta $\frac{1}{\lambda} = Q \ll \Lambda_b$ breakdown scale ~500 MeV



include long-range pion physics

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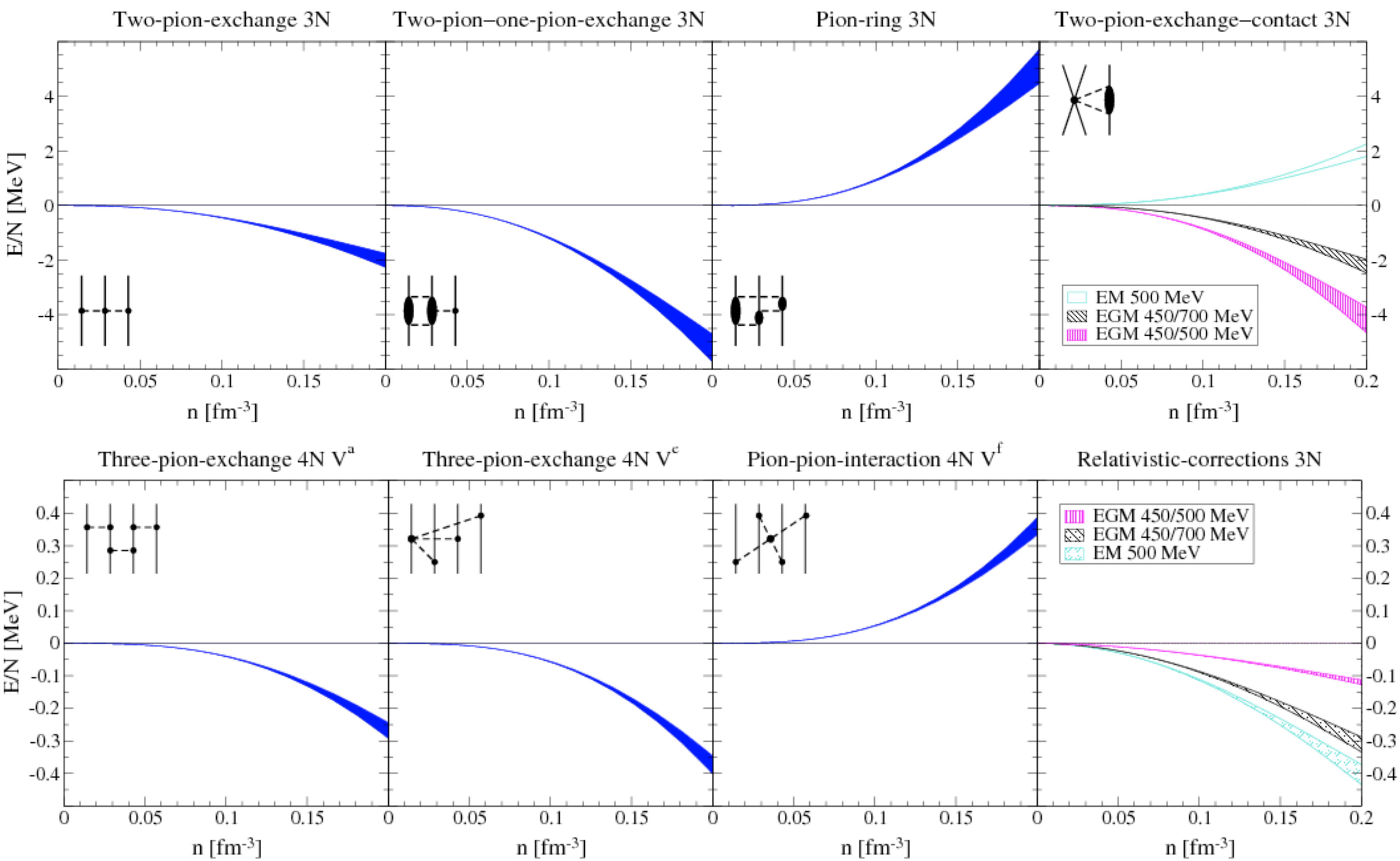
accuracy and obtain error estimates

expansion parameter ~ 1/3

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Kaiser, Machleidt, Meissner,…

Complete N^{3}LO calculation of neutron matter

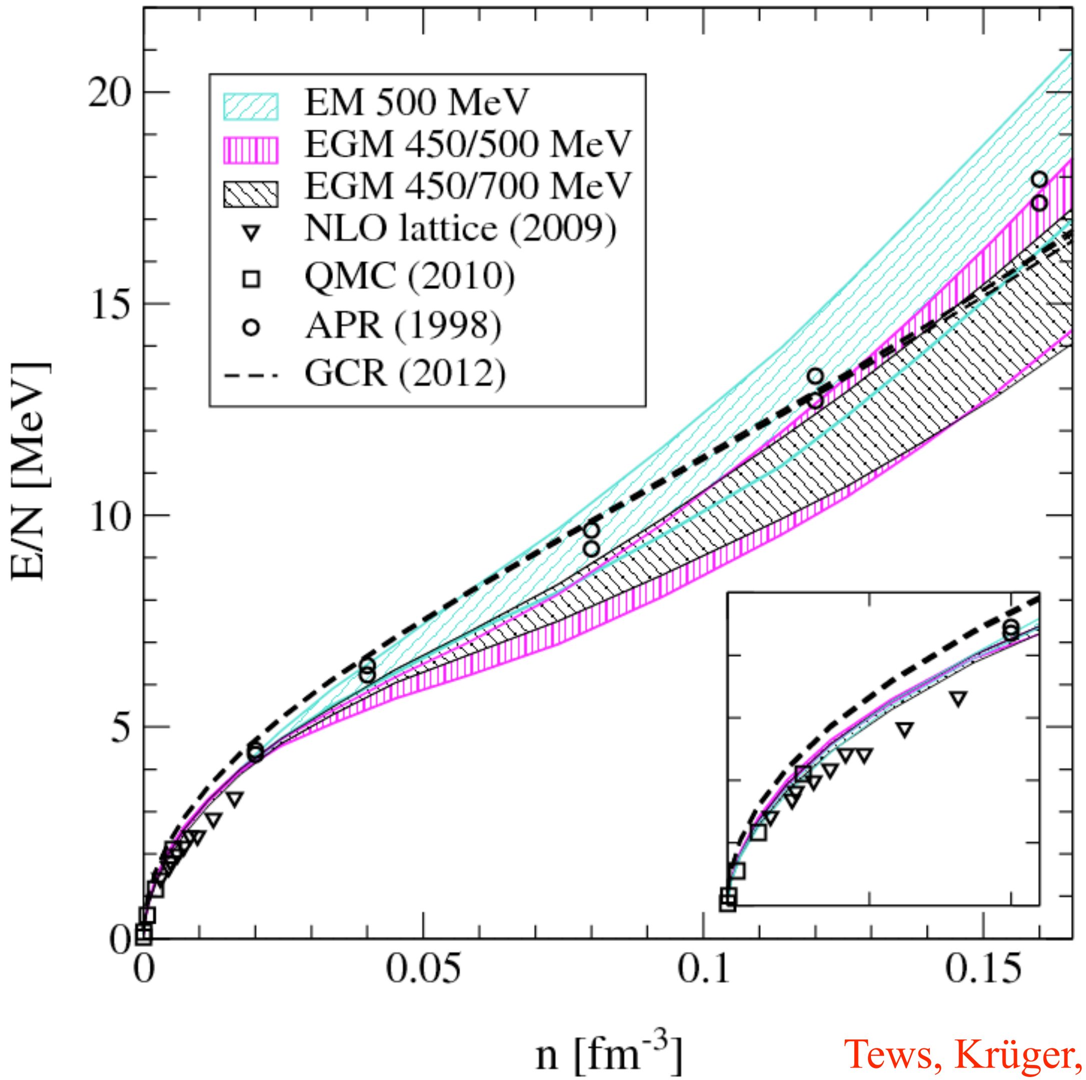


Tews, Krüger, Hebeler, AS, arXiv:1206.0025.

Complete N^3LO calculation of neutron matter

first complete N^3LO result

no RG evolution necessary, includes uncertainties from bare NN, 3N, 4N



The Bertsch problem

Tews, Krüger, Hebeler, AS, arXiv:1206.0025.

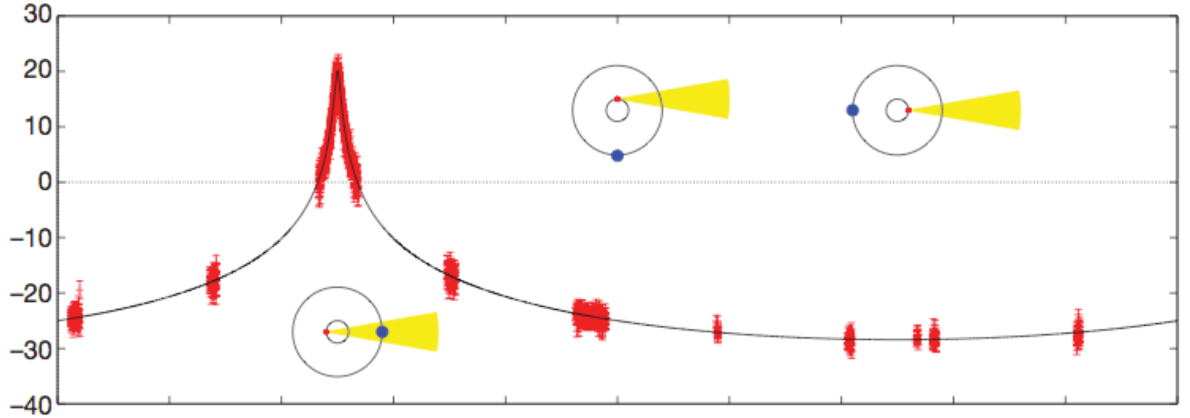
Discovery of the heaviest neutron star

A two-solar-mass neutron star measured using Shapiro delay

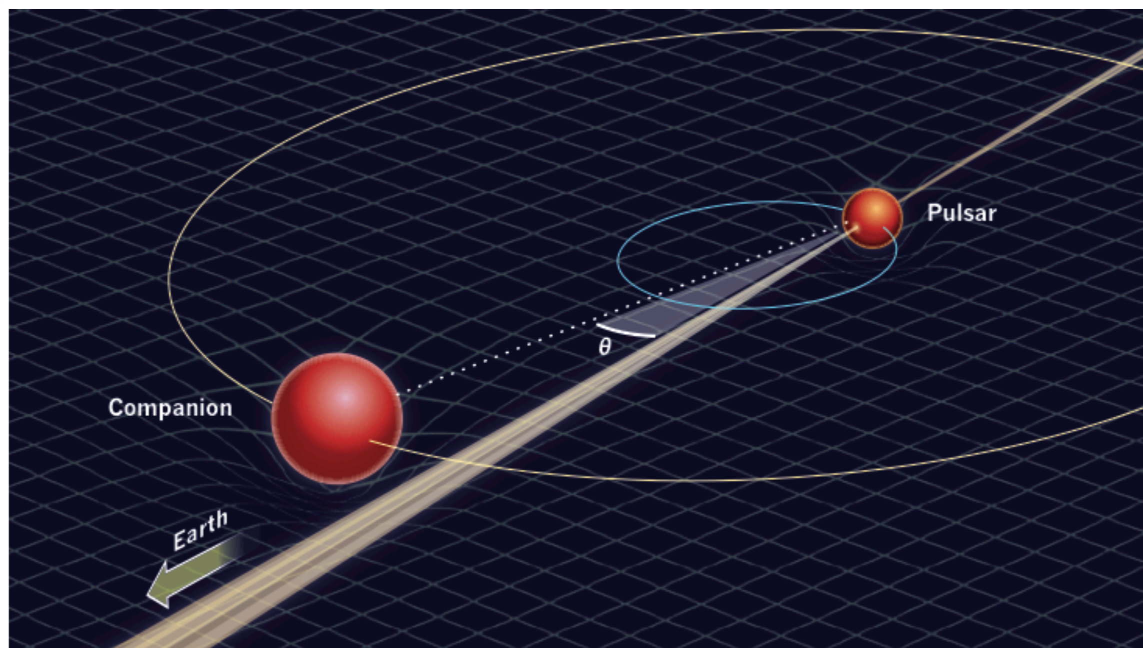
P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

Nature (2010)

direct measurement of neutron star mass from increase in signal travel time near companion



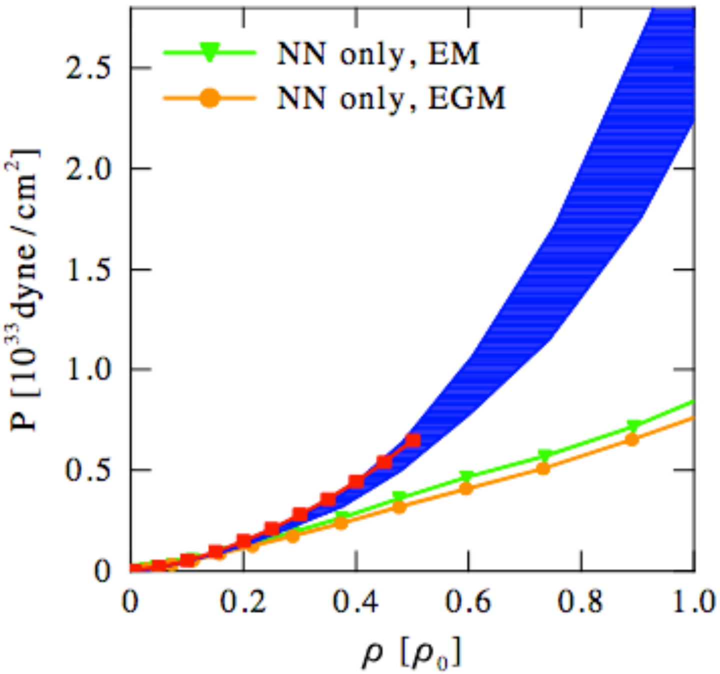
J1614-2230
most edge-on binary pulsar known (89.17°)
+ massive white dwarf companion (0.5 M_{sun})



heaviest neutron star with $1.97 \pm 0.04\ M_{sun}$

Impact on neutron stars Hebeler et al. (2010) and in prep.

Equation of state/pressure for neutron-star matter (includes small $Y_{e,p}$)



pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

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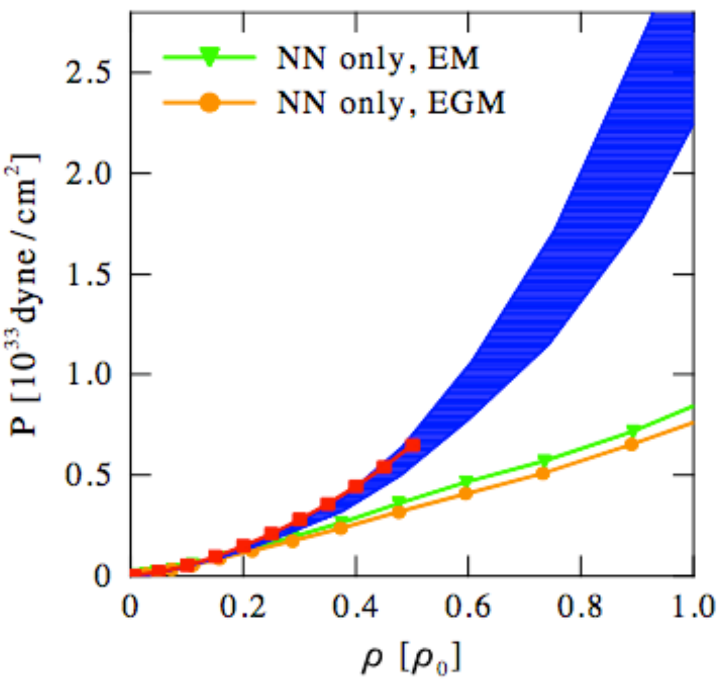
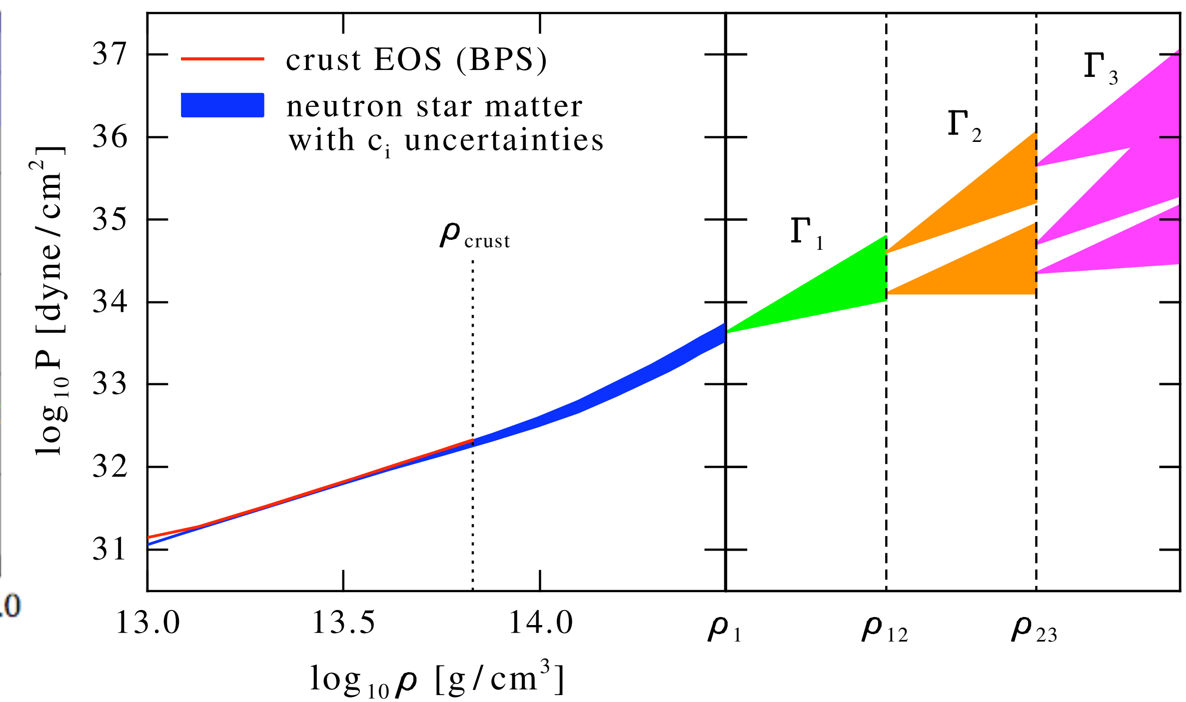
Equation of state/pressure for neutron-star matter (includes small $Y_{e,p}$)



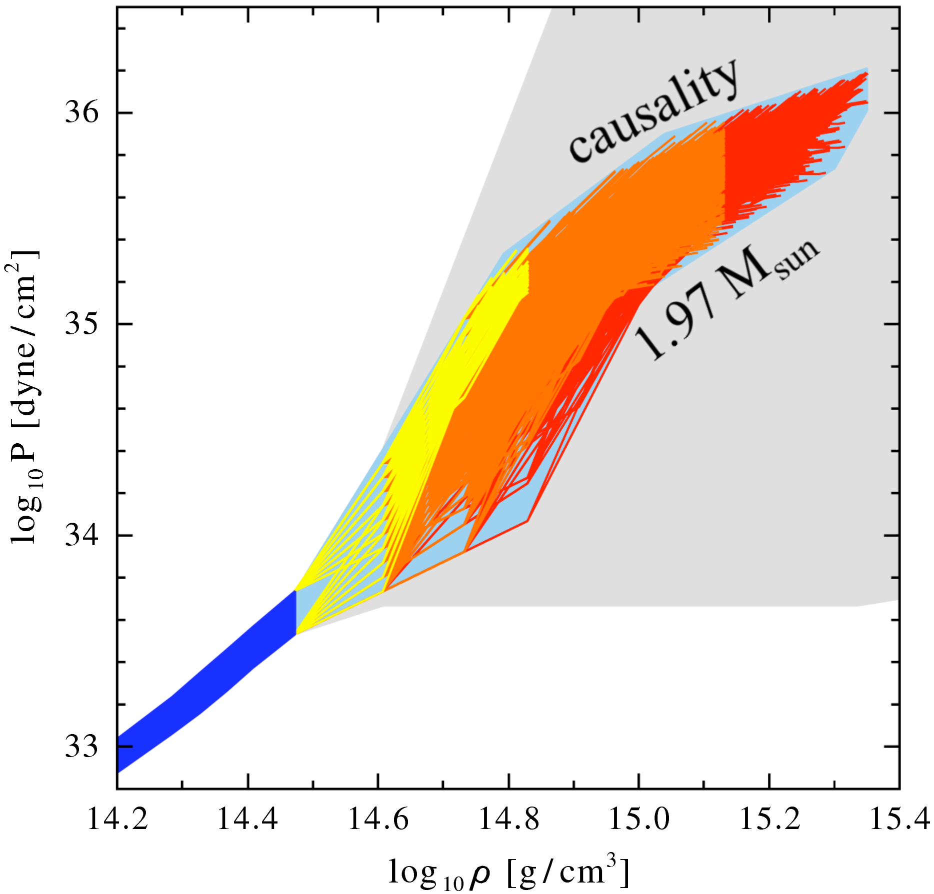


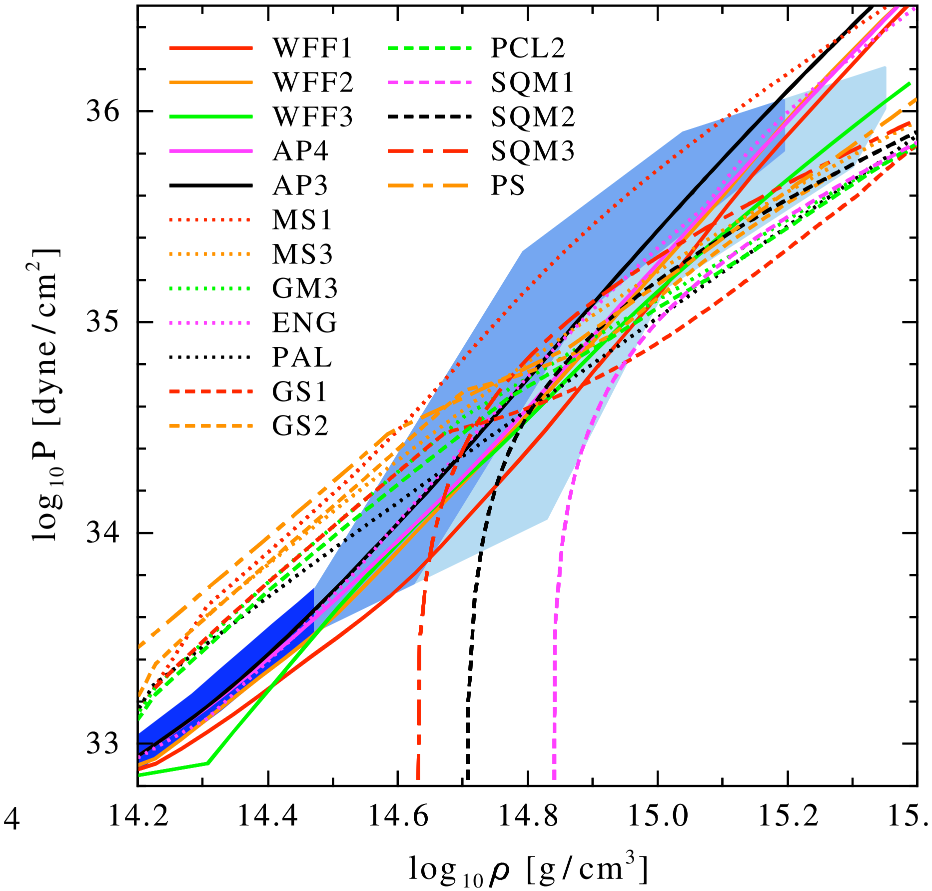
pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

extend uncertainty band to higher densities using piecewise polytropes allow for soft regions

Pressure of neutron star matter

constrain polytropes by causality and require to support 1.97 M_{sun} star

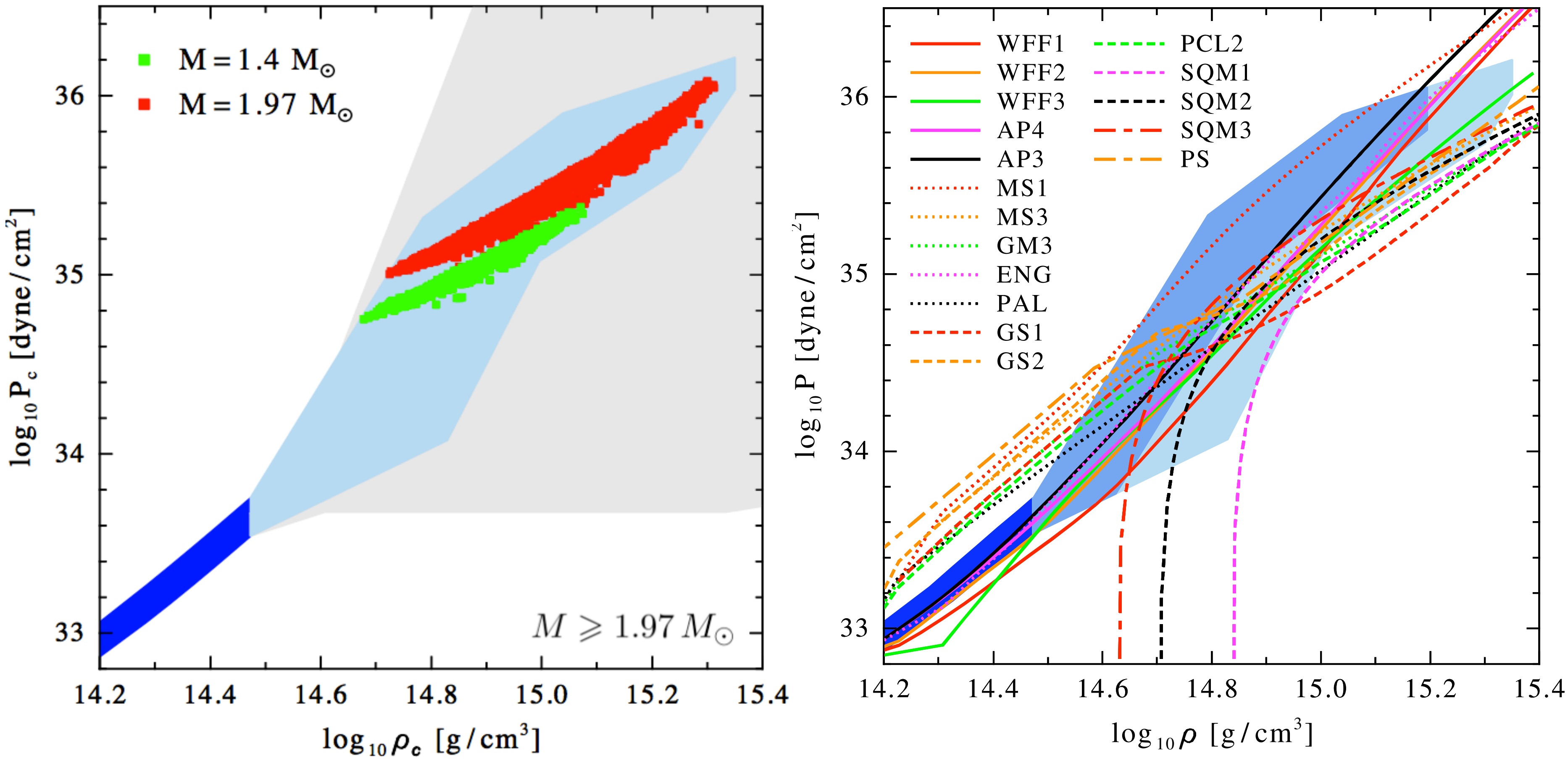




low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

Pressure of neutron star matter

constrain polytropes by causality and require to support 1.97 M_{sun} star

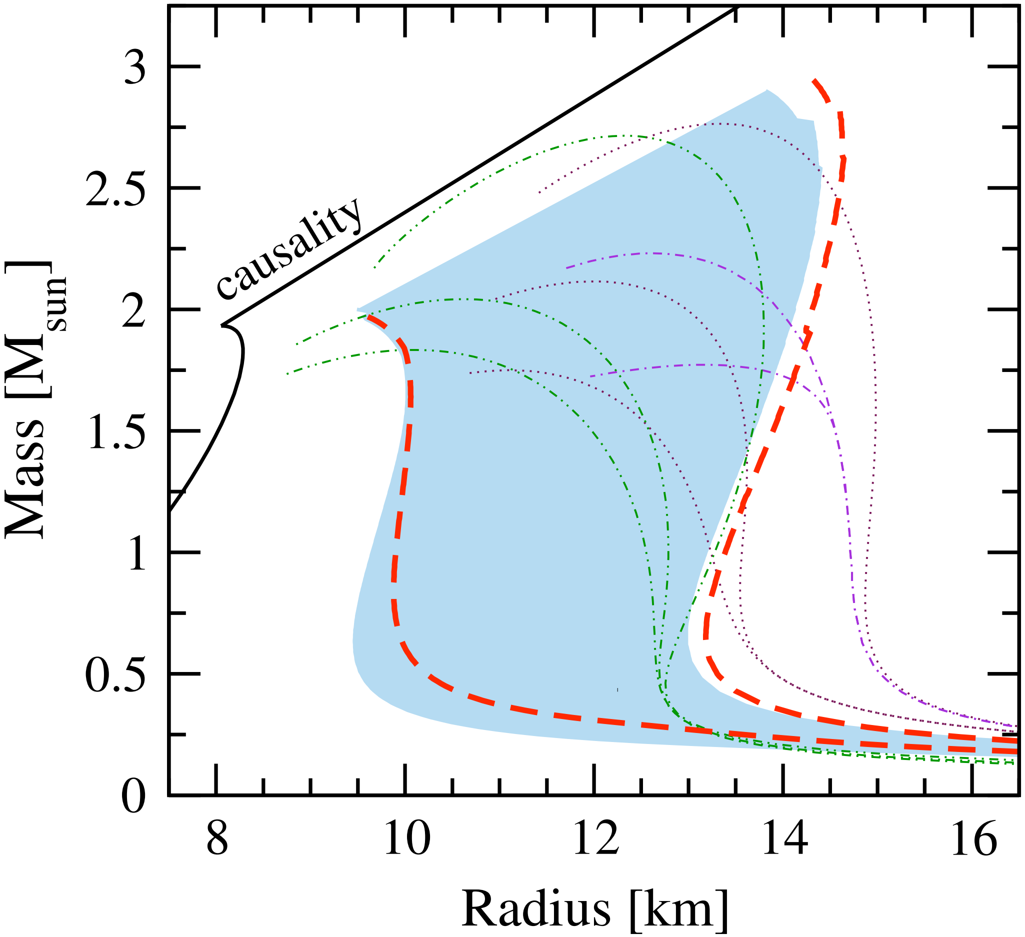


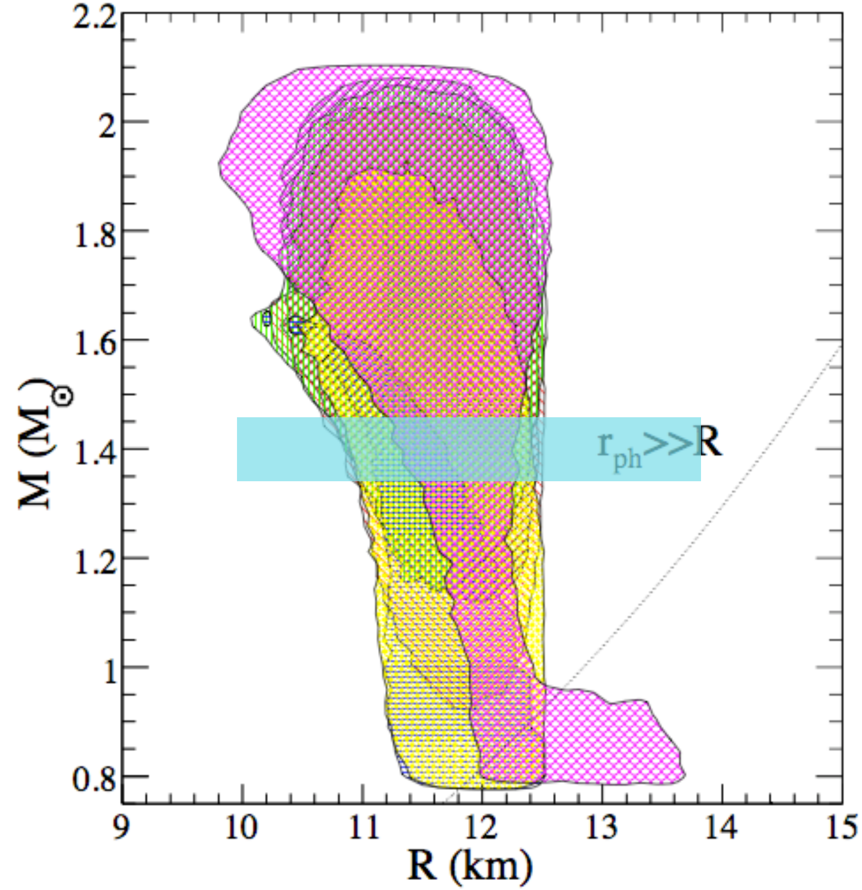
low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

central densities for 1.4 M_{sun} star: 1.7-4.4 ρ_0

Neutron star radius constraints

uncertainty from many-body forces and general extrapolation

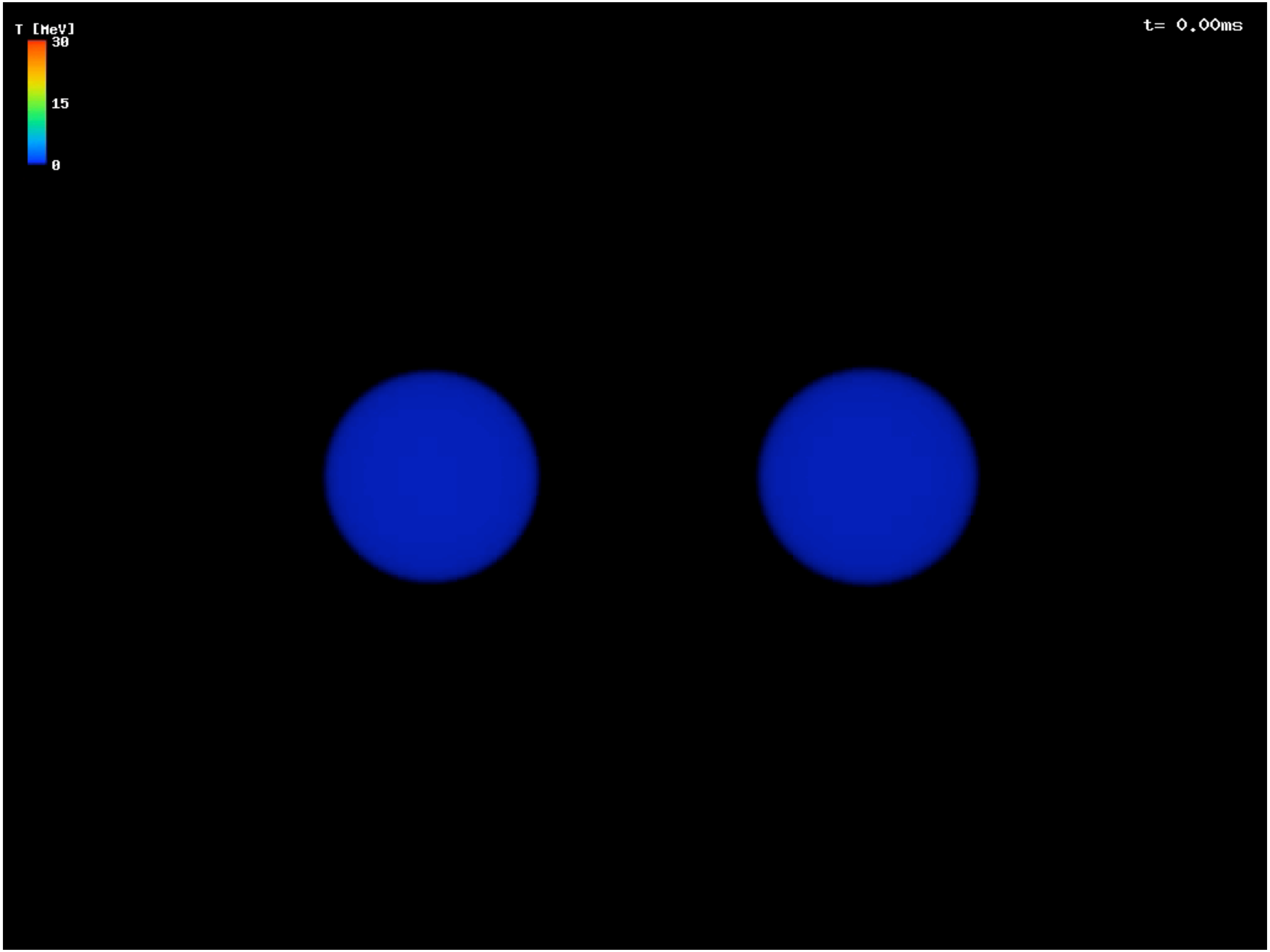




constrains neutron star radius: 9.9-13.8 km for M=1.4 M_{sun} (±15% !)

consistent with extraction from X-ray burst sources Steiner et al. (2010)
provides important constraints for EOS for core-collapse supernovae

Neutron-star mergers and gravitational waves



Neutron-star mergers and gravitational waves

explore sensitivity to neutron-rich matter in neutron-star merger and gw signal

Bauswein, Janka (2012) and A. Bauswein et al., arXiv:1204.1888.

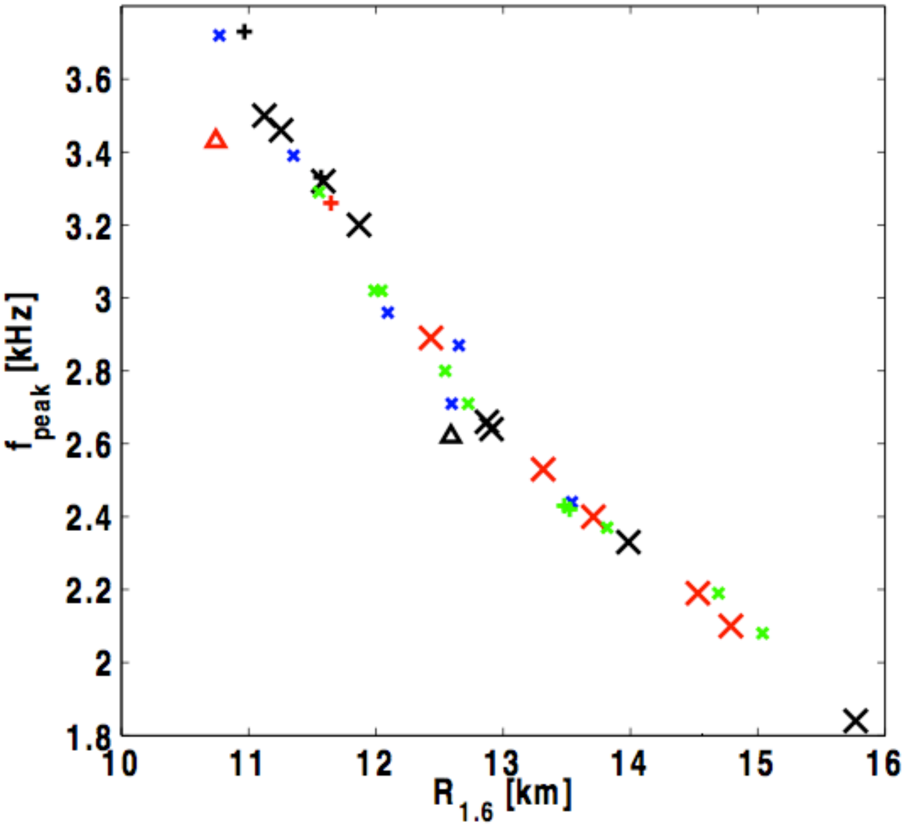


FIG. 10: Peak frequency of the postmerger GW emission versus the radius of a nonrotating NS with 1.6 $M_\odot$ for different EoSs. Symbols have the same meaning as in Fig. 8.

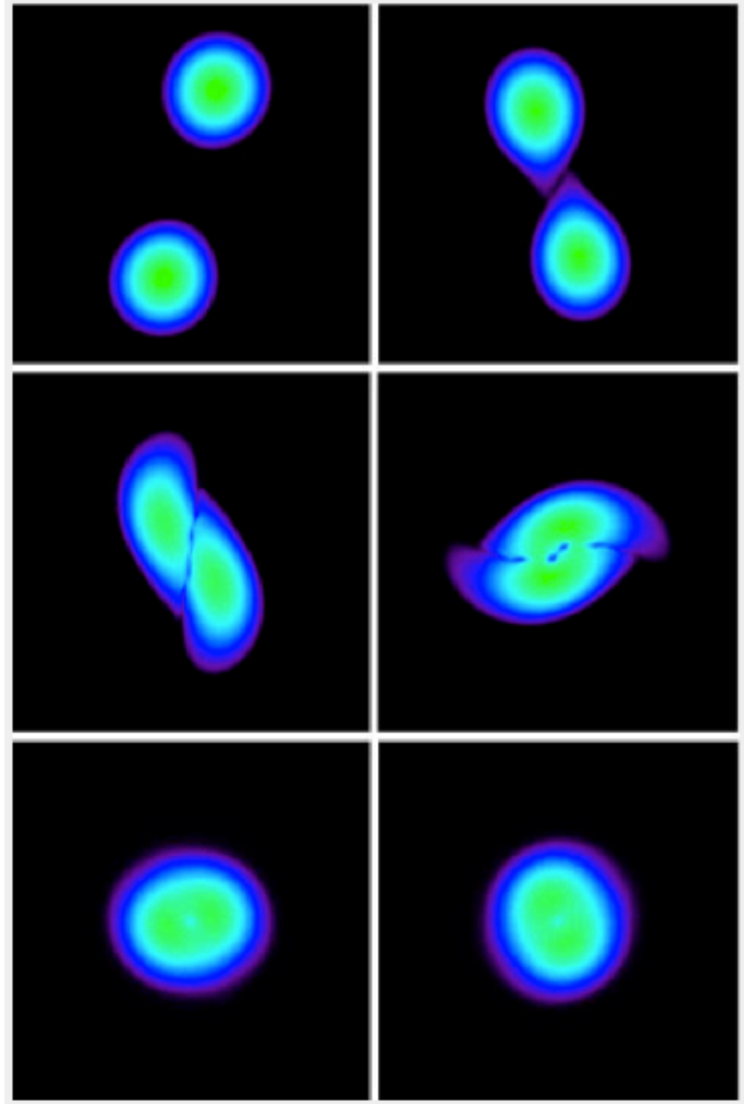


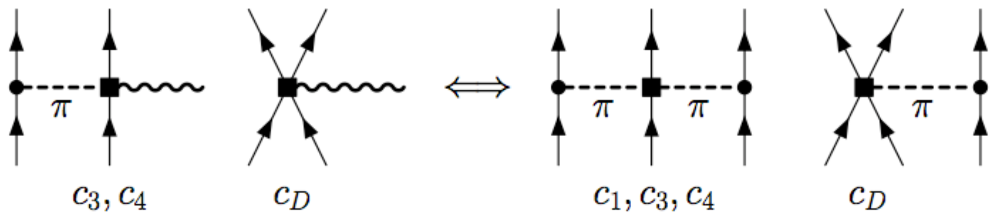
Fig. 1: Various snapshots of the collision of two neutron stars initially revolving around each other. The sequence simulated by the computer covers only 0.03 seconds. The two stars orbit each other counterclockwise (top left) and quickly come closer (top right). Finally they collide (centre left), merge (centre right), and form a dense, superheavy neutron star (bottom). Strong vibrations of the collision remnant are noticeable as deformations in east-west direction and in north-south direction (bottom panels). (Simulation: Andreas Bauswein and H.-Thomas Janka/MPA)

Electroweak interactions and 3N forces

weak axial currents couple to spin, similar to pions

two-body currents predicted by NN, 3N couplings to N^{3}LO

Park et al., Phillips,…



two-body analogue of Goldberger-Treiman relation

explored in light nuclei (reactions for SNO), but not for larger systems

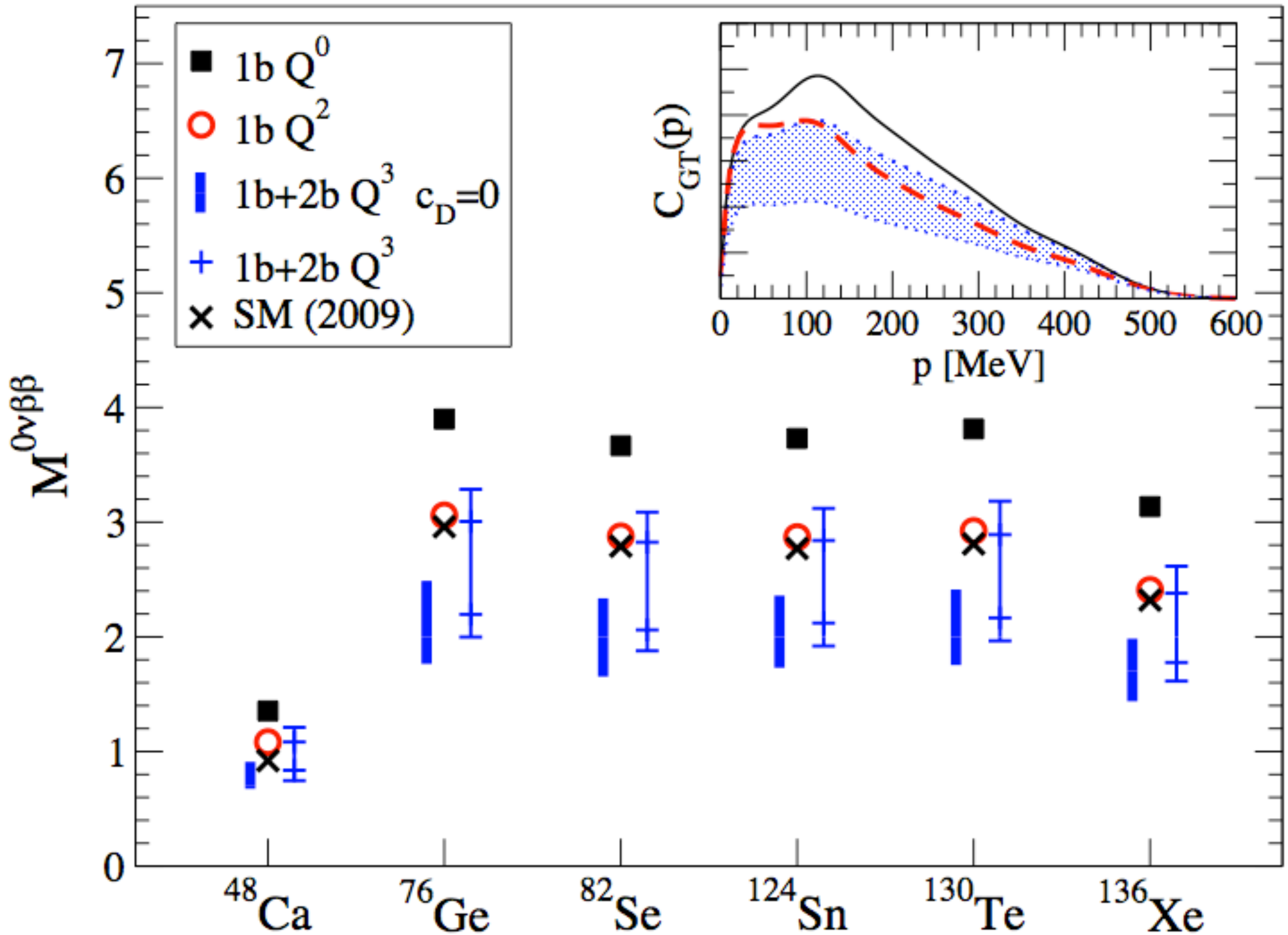
dominant contribution to Gamow-Teller transitions,
important in nuclei (Q~100 MeV)

3N couplings predict quenching of g_A (dominated by long-range part)
and predict momentum dependence (weaker quenching for larger p)
Menendez, Gazit, AS (2011)

Chiral EFT and 0νββ decay

Nuclear matrix elements for 0νββ decay based on chiral EFT operator
Menendez, Gazit, AS (2011)

Modest quenching because 0νββ decay probes higher momentum transfer



Summary

3N forces are a frontier for neutron-rich nuclei, matter, neutron stars:

key to explain why ^{24}O is the heaviest oxygen isotope

key for neutron-rich nuclei: Ca isotopes, N=28 and shell evolution

dominant uncertainty of neutron (star) matter below nuclear densities

predicts neutron skin with theoretical uncertainty comparable to exp.

constrains neutron star radii and equation of state for astrophysics

impact of 3N forces on global mass predictions?

exciting interactions with George, experiments and observations!